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THE INSTITUTION

OF

MECHANICAL ENGINEERS.

ESTABLISHED 1847.

PROCEEDINGS.

1904.

PARTS 1-2.

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The Institution of Mechanical Engineers.

PAST-PRESIDENTS.

George Stephenson, 1847–48. (*Deceased* 1848.)

Robert Stephenson, F.R.S., 1849–53. (*Deceased* 1859.)

Sir William Fairbairn, Bart., LL.D., F.R.S., 1854–55. (*Deceased* 1874.)

Sir Joseph Whitworth, Bart., D.C.L., LL.D., F.R.S., 1856–57, 1866. (*Deceased* 1887.)

John Penn, F.R.S., 1858–59, 1867–68. (*Deceased* 1878.)

James Kennedy, 1860. (*Deceased* 1886.)

The Right Hon. Lord Armstrong, C.B., D.C.L., LL.D., F.R.S., 1861–62, 1869. (*Deceased* 1900.)

Robert Napier, 1863–65. (*Deceased* 1876.)

John Ramsbottom, 1870–71. (*Deceased* 1897.)

Sir William Siemens, D.C.L., LL.D., F.R.S., 1872–73. (*Deceased* 1883.)

Sir Frederick J. Bramwell, Bart., D.C.L., LL.D., F.R.S., 1874–75. (*Deceased* 1903.)

Thomas Hawksley, F.R.S., 1876–77. (*Deceased* 1893.)

John Robinson, 1878–79. (*Deceased* 1902.)

Edward A. Cowper, 1880–81. (*Deceased* 1893.)

Percy G. B. Westmacott, 1882–83.

Sir Lowthian Bell, Bart., LL.D., F.R.S., 1884.

Jeremiah Head, 1885–86. (*Deceased* 1899.)

Sir Edward H. Carbutt, Bart., 1887–88.

Charles Cochrane, 1889. (*Deceased* 1898.)

Joseph Tomlinson, 1890–91. (*Deceased* 1894.)

Sir William Anderson, K.C.B., D.C.L., F.R.S., 1892–93. (*Deceased* 1898.)

Professor Alexander B. W. Kennedy, LL.D., F.R.S., 1894–95.

E. Windsor Richards, 1896–97.

Samuel Waite Johnson, 1898.

Sir William H. White, K.C.B., LL.D., D.Sc., F.R.S., 1899–1900.

William H. Maw, 1901–02.

The Institution of Mechanical Engineers.

OFFICERS.

1904.

PRESIDENT.

J. Hartley Wickstead,	Leeds.

PAST-PRESIDENTS.

Sir Lowthian Bell, Bart., LL.D., F.R.S.,	Northallerton.
Sir Edward H. Carbutt, Bart.,	London.
Samuel Waite Johnson,	Nottingham.
Professor Alexander B. W. Kennedy, LL.D., F.R.S.,	London.
William H. Maw,	London.
E. Windsor Richards,	Caerleon.
Percy G. B. Westmacott,	Ascot.
Sir William H. White, K.C.B., LL.D., D.Sc., F.R.S.,	London.

VICE-PRESIDENTS.

John A. F. Aspinall,	Manchester.
Edward B. Ellington,	London.
Arthur Keen,	Birmingham.
Edward P. Martin,	Dowlais.
T. Hurry Riches,	Cardiff.
A. Tannett-Walker,	Leeds.

MEMBERS OF COUNCIL.

Sir Benjamin Baker, K.C.B., K.C.M.G., LL.D., D.Sc., F.R.S.,	London.
Sir J. Wolfe Barry, K.C.B., LL.D., F.R.S.,	London.
Henry Chapman,	London.
Henry Davey,	London.
William Dean,	Folkestone.
H. Graham Harris,	London.
Edward Hopkinson, D.Sc.,	Manchester.
Henry A. Ivatt,	Doncaster.
Henry Lea,	Birmingham.
Sir William T. Lewis, Bart.,	Aberdare.
Michael Longridge,	Manchester.
James Mansergh, F.R.S.,	London.
Henry D. Marshall,	Gainsborough.
The Right Hon. William J. Pirrie, LL.D.,	Belfast.
Sir Thomas Richardson,	Hartlepool.
John F. Robinson,	London.
Mark H. Robinson,	Rugby.
John W. Spencer,	Newcastle-on-Tyne.
Sir John I. Thornycroft, LL.D., F.R.S.,	London.
John Tweedy,	Newcastle-on-Tyne.
Henry H. West,	Liverpool.

HON. TREASURER.

Harry Lee Millar.

AUDITOR.

Robert A. McLean, F.C.A.

SECRETARY.

Edgar Worthington,
The Institution of Mechanical Engineers,
Storey's Gate, St. James's Park, Westminster, S.W.
Telegraphic address:—*Mech, London.* Telephone:—*Westminster,* 264.

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THE INSTITUTION OF MECHANICAL ENGINEERS.

Memorandum of Association.

AUGUST 1878.

1st. The name of the Association is "THE INSTITUTION OF MECHANICAL ENGINEERS."

2nd. The Registered Office of the Association will be situate in England.

3rd. The objects for which the Association is established are:—

(A.) To promote the science and practice of Mechanical Engineering and all branches of mechanical construction, and to give an impulse to inventions likely to be useful to the Members of the Institution and to the community at large.

(B.) To enable Mechanical Engineers to meet and to correspond, and to facilitate the interchange of ideas respecting improvements in the various branches of mechanical science, and the publication and communication of information on such subjects.

(C.) To acquire and dispose of property for the purposes aforesaid.

(D.) To do all other things incidental or conducive to the attainment of the above objects or any of them.

4th. The income and property of the Association, from whatever source derived, shall be applied solely towards the promotion of the objects of the Association as set forth in this Memorandum of Association, and no portion thereof shall be paid or transferred directly or indirectly, by way of dividend, bonus, or otherwise howsoever, by way of profit to the persons who at any time are or have been Members of the Association, or to any of them, or to any person claiming through any of them: Provided that nothing herein contained shall prevent the payment in good faith of remuneration to any officers or servants of the Association, or to any Member of the Association, or other person, in return for any services rendered to the Association, or prevent the giving of privileges to the Members of the Association in attending the meetings of the Association, or prevent the borrowing of money (under such powers as the Association and the Council thereof may possess) from any Member of the Association, at a rate of interest not greater than five per cent. per annum.

5th. The fourth paragraph of this Memorandum is a condition on which a licence is granted by the Board of Trade to the Association in pursuance of Section 23 of the Companies Act 1867. For the purpose of preventing any evasion of the terms of the said fourth paragraph, the Board of Trade may from time to time, on the application of any Member of the Association, impose further conditions, which shall be duly observed by the Association.

6th. If the Association act in contravention of the fourth paragraph of this Memorandum, or of any such further conditions, the liability of every Member of the Council shall be unlimited; and the liability of every Member of the Association who has received any such dividend, bonus, or other profit as aforesaid, shall likewise be unlimited.

7th. Every Member of the Association undertakes to contribute to the Assets of the Association in the event of the same being wound up during the time that he is a Member, or within one year afterwards, for payment of the debts and liabilities of the Association contracted before the time at which he ceases to be a Member, and of the costs, charges, and expenses for winding up the same, and for the adjustment of the rights of the contributories amongst themselves, such amount as may be required not exceeding Five Shillings, or in case of his liability becoming unlimited such other amount as may be required in pursuance of the last preceding paragraph of this Memorandum.

8th. If upon the winding up or dissolution of the Association there remains, after the satisfaction of all its debts and liabilities, any property whatsoever, the same shall not be paid to or distributed among the Members of the Association, but shall be given or transferred to some other Institution or Institutions having objects similar to the objects of the Association, to be determined by the Members of the Association at or before the time of dissolution; or in default thereof, by such Judge of the High Court of Justice as may have or acquire jurisdiction in the matter.

Articles of Association.

FEBRUARY 1893.

(*Article* 23 *revised March* 1902.)

INTRODUCTION.

Whereas an Association called "The Institution of Mechanical Engineers" existed from 1847 to 1878 for objects similar to the objects expressed in the Memorandum of Association of the Association (hereinafter called "the Institution") to which these Articles apply;

And whereas the Institution was formed in 1878 for furthering and extending the objects of the former Institution, by a registered Association, under the Companies Acts 1862 and 1867;

And whereas terms used in these Articles are intended to have the same respective meanings as they have when used in those Acts, and words implying the singular number are intended to include the plural number, and *vice versâ*;

NOW THEREFORE IT IS HEREBY AGREED as follows:—

CONSTITUTION.

1. For the purpose of registration the number of members of the Institution is unlimited.

MEMBERS, ASSOCIATE MEMBERS, GRADUATES, ASSOCIATES, AND HONORARY LIFE MEMBERS.

2. The present Members of the Institution, and such other persons as shall be admitted in accordance with these Articles, and none others, shall be Members of the Institution, and be entered on the register as such.

3. Any person may become a Member of the Institution who shall be qualified and elected as hereinafter mentioned, and shall agree to become such Member, and shall pay the entrance fee and first subscription accordingly.

4. The qualification of Members shall be prescribed by the By-laws from time to time in force, as provided by the Articles.

5. The election of Members shall be conducted as prescribed by the By-laws from time to time in force, as provided by the Articles.

6. In addition to the persons already admitted as Graduates, Associates, and Honorary Life Members respectively, the Institution may admit such persons as may be qualified and elected in that behalf as Associate Members, Graduates, Associates, and Honorary Life Members respectively of the Institution, and may confer upon them such privileges as shall be prescribed by the By-laws from time to time in force, as provided by the Articles: provided that no Associate Member, Graduate, Associate, or Honorary Life Member shall be deemed to be a Member within the meaning of the Articles.

7. The qualification and mode of election of Associate Members, Graduates, Associates, and Honorary Life Members shall be prescribed by the By-laws from time to time in force, as provided by the Articles.

8. The rights and privileges of every Member, Associate Member, Graduate, Associate, or Honorary Life Member shall be personal to himself, and shall not be transferable or transmissible by his own act or by operation of law.

ENTRANCE FEES AND SUBSCRIPTIONS.

9. The Entrance Fees and Subscriptions of Members, Associate Members, Graduates, and Associates shall be prescribed by the By-laws from time to time in force, as provided by the Articles.

EXPULSION.

10. If any Member, Associate Member, Graduate, or Associate shall leave his subscription in arrear for two years, and shall fail to pay such arrears within three months after a written application has been sent to him by the Secretary, his name may be struck off the register by the Council at any time afterwards, and he shall thereupon cease to have any rights as a Member, Associate Member, Graduate, or Associate, but he shall nevertheless continue liable to pay the arrears of subscription due at the time of his name being so struck off: provided always that this regulation shall not be construed to compel the Council to remove any name, if they shall be satisfied the same ought to be retained.

11. The Council may refuse to continue to receive the subscriptions of any person who shall have wilfully acted in contravention of the regulations of the Institution, or who shall in the opinion of the Council have been guilty of such conduct as shall have rendered him unfit to continue to belong to the Institution; and may remove his name from the register, and he shall thereupon cease to be a Member, Associate Member, Graduate, or Associate (as the case may be) of the Institution.

GENERAL MEETINGS.

12. The General Meetings shall consist of the Ordinary Meetings, the Annual General Meeting, and of Special Meetings as hereinafter defined.

13. The Annual General Meeting shall take place in London in one of the first four months of every year. The Ordinary Meetings shall take place at such times and places as the Council shall determine.

14. A Special Meeting may be convened at any time by the Council, and shall be convened by them whenever a requisition signed by twenty Members or Associate Members of the Institution,

specifying the object of the Meeting, is left with the Secretary. If for fourteen days after the delivery of such requisition a Meeting be not convened in accordance therewith, the Requisitionists or any twenty Members or Associate Members of the Institution may convene a Special Meeting in accordance with the requisition. All Special Meetings shall be held in London.

15. Seven clear days' notice of every Meeting, specifying generally the nature of any special business to be transacted at any Meeting, shall be given to every person on the register of the Institution, except as provided by Article 35, and no other special business shall be transacted at such Meeting; but the non-receipt of such notice shall not invalidate the proceedings of such Meeting. No notice of the business to be transacted (other than such ballot lists as may be requisite in case of elections) shall be required in the absence of special business.

16. Special business shall include all business for transaction at a Special Meeting, and all business for transaction at every other Meeting, with the exception of the reading and confirmation of the Minutes of the previous Meeting, the election of Members, Associate Members, Graduates, and Associates, and the reading and discussion of communications as prescribed by the By-laws, or by any regulations of the Council made in accordance with the By-laws.

PROCEEDINGS AT GENERAL MEETINGS.

17. Twenty Members or Associate Members shall constitute a quorum for the purpose of a Meeting other than a Special Meeting. Thirty Members or Associate Members shall constitute a quorum for the purpose of a Special Meeting.

18. If within thirty minutes after the time fixed for holding the Meeting a quorum is not present, the Meeting shall be dissolved, and all matters which might, if a quorum had been present, have been done at a Meeting (other than a Special Meeting) so dissolved, may forthwith be done on behalf of the Meeting by the Council.

19. The President shall be Chairman at every Meeting, and in his absence one of the Vice-Presidents; and in the absence of all Vice-Presidents a Member of Council shall take the chair; and if no Member of Council be present and willing to take the chair, the Meeting shall elect a Chairman.

20. The decision of a General Meeting shall be ascertained by show of hands, unless, after the show of hands, a poll is forthwith demanded; and by a poll, when a poll is thus demanded. The manner of taking a show of hands or a poll shall be in the discretion of the Chairman; and an entry in the Minutes, signed by the Chairman, shall be sufficient evidence of the decision of the General Meeting. Each Member and Associate Member shall have one vote and no more. In case of equality of votes the Chairman shall have a second or casting vote: provided that this Article shall not interfere with the provisions of the By-laws as to election by ballot.

21. The acceptance or rejection of votes by the Chairman shall be conclusive for the purpose of the decision of the matter in respect of which the votes are tendered: provided that the Chairman may review his decision at the same Meeting, if any error be then pointed out to him.

BY-LAWS.

22. The By-laws set forth in the schedule to these Articles, and such altered and additional By-laws as shall be substituted or added as hereinafter mentioned, shall regulate all matters by the Articles left to be prescribed by the By-laws, and all matters which consistently with the Articles shall be made the subject of By-laws. Alterations in, and additions to, the By-laws, may be made only by resolution of the Members and Associate Members at an Annual General Meeting, after notice of the proposed alteration or addition has been announced at the previous Ordinary Meeting, and not otherwise.

COUNCIL.

23. The Council of the Institution shall be chosen from the Members only, and shall consist of one President, six Vice-Presidents, twenty-one ordinary Members of Council, and of the Past-Presidents. The President, two Vice-Presidents, and seven Members of Council (other than Past-Presidents), shall retire at each Annual General Meeting, but shall be eligible for re-election. The Vice-Presidents and Members of Council to retire each year shall, unless the Council agree otherwise among themselves, be chosen from those who have been longest in office, and in cases of equal seniority shall be determined by ballot.

24. The election of a President, Vice-Presidents, and Members of Council, to supply the place of those retiring at the Annual General Meeting, shall be conducted in such manner as shall be prescribed by the By-laws from time to time in force, as provided by the Articles.

25. The Council may supply any casual vacancy in the Council (including any casual vacancy in the office of President) which shall occur between one Annual General Meeting and another; and the President, Vice-Presidents, or Members of Council so appointed by the Council shall retire at the succeeding Annual General Meeting. Vacancies not filled up at any such Meeting shall be deemed to be casual vacancies within the meaning of this Article.

OFFICERS.

26. The Treasurer, Secretary, and other employés of the Institution shall be appointed and removed in the manner prescribed by the By-laws from time to time in force, as provided by the Articles. Subject to the express provisions of the By-laws, the officers and servants of the Institution shall be appointed and removed by the Council.

27. The powers and duties of the officers of the Institution shall, subject to any express provision in the By-laws, be determined by the Council.

POWERS AND PROCEDURE OF COUNCIL.

28. The Council may regulate their own procedure, and delegate any of their powers and discretions to any one or more of their body, and may determine their own quorum: if no other number is prescribed, three members of Council shall form a quorum.

29. The Council shall manage the property, proceedings, and affairs of the Institution, in accordance with the By-laws from time to time in force.

30. The Treasurer may, with the consent of the Council, invest in the name of the Institution any moneys not immediately required for the purposes of the Institution in or upon any of the following investments (that is to say):—

(A) The Public Funds, or Government Stocks of the United Kingdom, or of any Foreign or Colonial Government guaranteed by the Government of the United Kingdom.

(B) Real or Leasehold Securities, or in the purchase of real or leasehold properties in Great Britain or Ireland.

(C) Debentures, Debenture Stock, or Guaranteed or Preference Stock, of any Company incorporated by special Act of Parliament, the ordinary Shareholders whereof shall at the time of such investment be in actual receipt of half-yearly or yearly dividends.

(D) Stocks, Shares, Debentures, or Debenture Stock of any Railway, Canal, or other Company, the undertaking whereof is leased to any Railway Company at a fixed or fixed minimum rent.

(E) Stocks, Shares, or Debentures of any East Indian Railway or other Company, which shall receive a contribution from His Majesty's East Indian Government of a fixed annual percentage on their capital, or be guaranteed a fixed annual dividend by the same Government.

(F) The security of rates levied by any corporate body empowered to borrow money on the security of rates, where such borrowing has been duly authorised by Act of Parliament.

31. The Council may, with the authority of a resolution of the Members and Associate Members in General Meeting, borrow moneys for the purposes of the Institution on the security of the property of the Institution, or otherwise at their discretion.

32. No act done by the Council, whether *ultra vires* or not, which shall receive the express or implied sanction of the Members and Associate Members in General Meeting, shall be afterwards impeached by any member of the Institution on any ground whatsoever, but shall be deemed to be an act of the Institution.

NOTICES.

33. A notice may be served by the Council upon any Member, Associate Member, Graduate, Associate, or Honorary Life Member, either personally or by sending it through the post in a prepaid letter addressed to him at his registered place of abode.

34. Any notice, if served by post, shall be deemed to have been served at the time when the letter containing the same would be delivered in the ordinary course of the post; and in proving such service it shall be sufficient to prove that the letter containing the notice was properly addressed and put into the post office.

35. No Member, Associate Member, Graduate, Associate, or Honorary Life Member, not having a registered address within the United Kingdom, shall be entitled to any notice; and all proceedings may be had and taken without notice to such member, in the same manner as if he had had due notice.

By-laws.

(*Last Revision, February* 1894.)

MEMBERSHIP.

1. Candidates for admission as Members must be persons not under twenty-five years of age, who, having occupied during a sufficient period a responsible position in connection with the practice or science of Engineering, may be considered by the Council to be qualified for election.

2. Candidates for admission as Associate Members must be persons not under twenty-five years of age, who, being engaged in such work as is connected with the practice or science of Engineering, may be considered by the Council to be qualified for election, though not yet to occupy positions of sufficient responsibility, or otherwise not yet to be eligible, for admission as Members. They may afterwards be transferred at the discretion of the Council to the class of Members.

3. Candidates for admission as Graduates must be persons holding subordinate situations, and not under eighteen years of age. They must furnish evidence of training in the principles as well as in the practice of Engineering. Before attaining the age of twenty-six years, those elected after 1892 must apply for election as Members, Associate Members, or Associates, if they desire to remain connected with the Institution; they may not continue Graduates after attaining the age of twenty-six.

4. Candidates for admission as Associates must be persons not under twenty-five years of age, who from their scientific attainments or position in society may be considered eligible by the Council. They may afterwards be transferred at the discretion of the Council to the class of Associate Members or of Members.

5. The Council shall have the power to nominate as Honorary Life Members persons of eminent scientific acquirements, who in their opinion are eligible for that position.

6. The Members, Associate Members, Graduates, Associates, and Honorary Life Members shall have notice of and the privilege to attend all Meetings; but Members and Associate Members only shall be entitled to vote thereat.

7. The abbreviated distinctive Titles for indicating the connection with the Institution of Members, Associate Members, Graduates, Associates, or Honorary Life Members thereof, shall be the following:—for Members, M. I. Mech. E.; for Associate Members, A. M. I. Mech. E.; for Graduates, G. I. Mech. E.; for Associates, A. I. Mech. E.; for Honorary Life Members, Hon. M. I. Mech. E.

8. Subject to such regulations as the Council may from time to time prescribe, any Member, Associate Member, or Associate may upon application to the Secretary obtain a Certificate of his membership or other connection with the Institution. Every such certificate shall remain the property of, and shall on demand be returned to, the Institution.

ENTRANCE FEES AND SUBSCRIPTIONS.

9. Each Member shall pay an Annual Subscription of £3, and on election an Entrance Fee of £2.

10. Each Associate Member shall pay an Annual Subscription of £2 10*s*., and on election an Entrance Fee of £1. If afterwards transferred by the Council to the class of Members, he shall pay on transference 10*s*. additional subscription for the current year, and £1 additional entrance fee.

11. Each Graduate shall pay an Annual Subscription of £1 10*s*., but no Entrance Fee. Any Graduate elected prior to 1893, if transferred by the Council to the class of Associate Members, shall pay on transference £1 additional subscription for the current year, but no additional entrance fee; if transferred direct to the class of Members, he shall pay on transference £1 10*s*. additional subscription for the current year, and £1 additional entrance fee.

12. Each Associate shall pay an Annual Subscription of £2 10s., and on election an Entrance Fee of £1. If afterwards transferred by the Council to the class of Associate Members, he shall pay on transference no additional subscription or entrance fee. If transferred direct to the class of Members, he shall pay on transference 10s. additional subscription for the current year, and £1 additional entrance fee; except Associates elected prior to 1893, who shall pay no additional entrance fee on transference.

13. All subscriptions shall be payable in advance, and shall become due on the 1st day of January in each year; and the first subscription of Members, Associate Members, Graduates, and Associates, shall date from the 1st day of January in the year of their election.

14. In the case of Members, Associate Members, Graduates, or Associates, elected in the last three months of any year, the first subscription shall cover both the year of election and the succeeding year.

15. Any Member, Associate Member, or Associate, whose subscription is not in arrear, may at any time compound for his subscription for the current and all future years by the payment of Fifty Pounds, if paid in any one of the first five years of his membership. If paid subsequently, the sum of Fifty Pounds shall be reduced by One Pound per annum for every year of membership after five years. All compositions shall be deemed to be capital moneys of the Institution.

16. The Council may at their discretion reduce or remit the annual subscription, or the arrears of annual subscription, of any Member or Associate Member who shall have been a subscribing member of the Institution for twenty years, and shall have become unable to continue the annual subscription provided by these By-laws.

17. No Proceedings or Ballot Lists or Certificates shall be sent to Members, Associate Members, Graduates, or Associates, who are in

arrear with their subscriptions more than twelve months, and whose subscriptions have not been remitted by the Council as hereinbefore provided.

ELECTION OF MEMBERS, ASSOCIATE MEMBERS, GRADUATES, AND ASSOCIATES.

18. A recommendation for admission according to Form A or B in the Appendix shall be forwarded to the Secretary, and by him be laid before the next Meeting of the Council. The recommendation must be signed by not less than five Members or Associate Members if the application be for admission as a Member or Associate Member or Associate, and by three Members or Associate Members if it be for a Graduate.

19. All elections shall take place by ballot, four-fifths of the votes given being necessary for election.

20. All applications for admission shall be communicated by the Secretary to the Council for their approval previous to being inserted in the ballot list for election, and the approved ballot list shall be signed by the President and forwarded to the Members and Associate Members. The name of any Candidate approved by the Council for admission as an Associate Member or an Associate shall not be inserted in the ballot list until he has signed the Form C in the Appendix. The ballot list shall specify the name, occupation, and address of the Candidates, and also by whom proposed and seconded. The lists shall be opened only in the presence of the Council on the day of election, by a Committee to be appointed for that purpose.

21. The Elections shall take place at the General Meetings only.

22. When the proposed Candidate is elected, the Secretary shall give him notice thereof according to Form D; but his name shall not be added to the register of the Institution until he shall have paid his Entrance Fee and first Annual Subscription, and signed the Form E in the Appendix.

23. In case of non-election, no mention thereof shall be made in the Minutes, nor any notice given to the unsuccessful Candidate.

24. An Associate Member desirous of being transferred to the class of Members, or an Associate to the class of Associate Members or of Members, shall forward to the Secretary a recommendation according to Form F in the Appendix, signed by not less than five Members or Associate Members, which shall be laid before the next meeting of Council for their approval. On their approval being given, the Secretary shall notify the same to the Candidate according to Form G; but his name shall not be added to the list of Members or Associate Members until he shall have signed the Form H, and shall have paid the additional entrance fee (if any), and the additional subscription (if any) for the current year.

ELECTION OF PRESIDENT, VICE-PRESIDENTS, AND MEMBERS OF COUNCIL.

25. Candidates shall be put in nomination at the General Meeting preceding the Annual General Meeting, when the Council are to present a list of their retiring Members who offer themselves for re-election; any Member or Associate Member shall then be entitled to add to the list of Candidates. The ballot list of the proposed names shall be forwarded to the Members and Associate Members. The ballot lists shall be opened only in the presence of the Council on the day of election, by a Committee to be appointed for that purpose.

APPOINTMENT AND DUTIES OF OFFICERS.

26. The Treasurer shall be a Banker, and shall hold the uninvested funds of the Institution, except the moneys in the hands of the Secretary for current expenses. He shall be appointed by the Members and Associate Members at a General or Special Meeting, and shall hold office at the pleasure of the Council.

27. The Secretary of the Institution shall be appointed, as and when a vacancy occurs, by the Members and Associate Members at a General or Special Meeting, and shall be removable by the Council upon six months' notice from any day. The Secretary shall give the same notice. The Secretary shall devote the whole of his time to the work of the Institution, and shall not engage in any other business or profession.

28. It shall be the duty of the Secretary, under the direction of the Council, to conduct the correspondence of the Institution; to attend all meetings of the Institution, and of the Council, and of Committees; to take minutes of the proceedings of such meetings; to read the minutes of the preceding meetings, and all communications that he may be ordered to read; to superintend the publication of such papers as the Council may direct; to have the charge of the library; to direct the collection of the subscriptions, and the preparation of the account of expenditure of the funds; and to present all accounts to the Council for inspection and approval. He shall also engage (subject to the approval of the Council) and be responsible for all persons employed under him, and set them their portions of work and duties. He shall conduct the ordinary business of the Institution, in accordance with the Articles and By-laws and the directions of the President and Council; and shall refer to the President in any matters of difficulty or importance, requiring immediate decision.

MISCELLANEOUS.

29. All Papers shall be submitted to the Council for approval, and after their approval shall be read by the Secretary at the General Meetings, or by the Author with the consent of the Council; or, if so directed by the Council, shall be printed in the Proceedings without having been read at a General Meeting.

30. All books, drawings, communications, &c., shall be accessible to the members of the Institution at all reasonable times.

31. All communications to the Meetings shall be the property of the Institution, and be published only by the authority of the Council.

32. None of the property of the Institution—books, drawings, &c.—shall be taken out of the premises of the Institution without the consent of the Council.

33. All donations to the Institution shall be enumerated in the Annual Report of the Council presented to the Annual General Meeting.

34. The General Meetings shall be conducted as far as practicable in the following order:—

1st. The Chair to be taken at such hour as the Council may direct from time to time.

2nd. The Minutes of the previous Meeting to be read by the Secretary, and, after being approved as correct, to be signed by the Chairman.

3rd. The Ballot Lists, previously opened by the Council, to be presented to the Meeting, and the new Members, Associate Members, Graduates, and Associates elected to be announced.

4th. Papers approved by the Council to be read by the Secretary, or by the Author with the consent of the Council.

35. Each Member or Associate Member shall have the privilege of introducing one friend to any of the Meetings; but, during such portion of any meeting as may be devoted to any business connected with the management of the Institution, visitors shall be requested by the Chairman to withdraw, if any Member or Associate Member asks that this shall be done.

36. Every Member, Associate Member, Graduate, Associate, or Visitor, shall write his name and residence in a book to be kept for the purpose, on entering each Meeting.

37. The President shall ex officio be member of all Committees of Council.

38. Seven clear days' notice at least shall be given of every meeting of the Council. Such notice shall specify generally the business to be transacted by the meeting. No business involving the expenditure of the funds of the Institution (except by way of payment of current salaries and accounts) shall be transacted at any Council meeting unless specified in the notice convening the meeting.

39. The Council shall present the yearly accounts to the Annua General Meeting, after being audited by a professional accountant, who shall be appointed annually by the Members and Associate Members at a General or a Special Meeting, at a remuneration to be then fixed by the Members and Associate Members.

40. Any member wishing to have a copy of the Papers sent to him for consideration beforehand can do so by sending in his name once in each year to the Secretary; and a copy of all Papers shall then be forwarded to him as early as possible prior to the date of the Meeting at which they are intended to be read.

41. At any Meeting of the Institution any member shall be at liberty to re-open the discussion upon any Paper which has been read or discussed at the preceding Meeting; provided that he signifies his intention to the Secretary at least one month previously to the Meeting, and that the Council decide to include it in the notice of the Meeting as part of the business to be transacted.

APPENDIX.

FORM A.

Mr. being years of age, and desirous of admission into The Institution of Mechanical Engineers, we, the undersigned proposer and seconder from our personal knowledge, and the three other signers from trustworthy information, propose and recommend him as a proper person to belong to the Institution.

Witness our hands, this day of

Members or Associate Members.

FORM B.

Mr. born on being desirous of admission into The Institution of Mechanical Engineers, we, the undersigned proposer and seconder from our personal knowledge, and the other signer or signers from trustworthy information, propose and recommend him as a proper person to become a Graduate thereof.

Witness our hands, this day of

Members or Associate Members.

FORM C.

If elected an of The Institution of Mechanical Engineers, I, the undersigned, do hereby engage to ratify my election by signing the form of agreement (E) and paying the Entrance Fee and Annual Subscription in conformity with the By-laws.

Witness my hand, this day of

FORM D.

Sir,—I have to inform you that on the you were elected a of The Institution of Mechanical Engineers. For the ratification of your election in conformity with the rules, it is requisite that the enclosed form be returned to me with your signature, and that your Entrance Fee and first Annual Subscription be paid, the amounts of which are and respectively. If these be not received within two months from the present date, the election will become void.

I am, Sir, Your obedient servant,

Secretary.

FORM E.

I, the undersigned, being elected a of The Institution of Mechanical Engineers, do hereby agree that I will be governed by the regulations of the said Institution, as they are now formed or as they may hereafter be altered; that I will advance the objects of the Institution as far as shall be in my power, and will attend the Meetings thereof as often as I conveniently can: provided that, whenever I shall signify in writing to the Secretary that I am desirous of withdrawing from the Institution, I shall (after the payment of any arrears which may be due by me at that period) be free from this obligation.

Witness my hand, this day of

FORM F.

Mr. being years of age, and desirous of being transferred into the class of of The Institution of Mechanical Engineers, we, the undersigned, from our personal knowledge recommend him as a proper person to be so transferred by the Council.

Witness our hands, this day of

Members or Associate Members.

FORM G.

Sir,—I have to inform you that the Council have approved of your being transferred to the class of of The Institution of Mechanical Engineers. For the ratification of your transference in conformity with the rules, it is requisite that the enclosed form be returned to me with your signature, and that your additional Entrance Fee and additional Annual Subscription for the current year be paid, the amounts of which are and respectively. If these be not received within two months from the present date, the transference will become void.

I am, Sir, Your obedient servant,

Secretary.

FORM H.

I, the undersigned, having been transferred to the class of of The Institution of Mechanical Engineers, do hereby agree that I will be governed by the regulations of the said Institution, as they now exist, or as they may hereafter be altered; that I will advance the objects of the Institution as far as shall be in my power, and will attend the Meetings thereof as often as I conveniently can: provided that, whenever I shall signify in writing to the Secretary that I am desirous of withdrawing from the Institution, I shall (after the payment of any arrears which may be due by me at that period) be free from this obligation.

Witness my hand, this day of

The Institution of Mechanical Engineers.

PROCEEDINGS.

15th January 1904.

An Ordinary General Meeting was held at the Institution on Friday, 15th January 1904, at Eight o'clock p.m.; J. Hartley Wicksteed, Esq., President, in the chair.

The Minutes of the previous Meeting were read and confirmed.

The President announced that, in accordance with the Rules of the Institution, the President, two Vice-Presidents, and seven Members of Council, would retire at the ensuing Annual General Meeting; and the list of those retiring was as follows:—

PRESIDENT.	
J. Hartley Wicksteed,	Leeds.
VICE-PRESIDENTS.	
Edward B. Ellington,	London.
T. Hurry Riches,	Cardiff.
MEMBERS OF COUNCIL.	
Sir Benjamin Baker, K.C.B., K.C.M.G., LL.D., D.Sc., F.R.S.,	London.
Sir J. Wolfe Barry, K.C.B., LL.D., F.R.S.,	London.
Henry Chapman,	London.
Edward Hopkinson, D.Sc.,	Manchester.
Henry A. Ivatt,	Doncaster.
Henry D. Marshall,	Gainsborough.
Sir John I. Thornycroft, LL.D., F.R.S.,	London.

All the foregoing had offered themselves for re-election, and had been nominated by the Council.

The following Nominations had also been made by the Council for the election at the Annual General Meeting:—

Election as Member.	MEMBERS OF COUNCIL.	
1877.	Lt.-Colonel R. E. B. CROMPTON, C.B.,	Chelmsford.
1888.	JAMES ROWAN,	Glasgow.
1898.	HAY F. DONALDSON,	Woolwich.

All of the above had consented to the Nomination.

The PRESIDENT reminded the Meeting that, according to the Rules of the Institution, any Member or Associate Member was then entitled to add to the list of candidates.

No other names being added, the President announced that the foregoing names would accordingly constitute the nomination list for the Election of Officers at the Annual General Meeting.

The PRESIDENT announced that the Ballot Lists for the election of New Members had been opened by a Committee of the Council, and that the following forty-three candidates were found to be duly elected:—

MEMBERS.

COATES, ALFRED,	Darlington.
DAVIES, SIDNEY,	Luton.
GRANGE, ROBERT BURNS,	Sydney.
READ, HENRY GEORGE,	Kharkov, Russia.
WALLIS, GEORGE PEARSON,	Leeds.

ASSOCIATE MEMBERS.

ALLAN, ALEXANDER BUCHANAN,	Ipswich.
BING, HERBERT,	London.
BROUGHTON, FREEMAN,	Manchester.
BUTLER, GEORGE HENRY,	Bristol.

Courts, William Charles,	Manchester.
Cunningham, Philips Daves Glendower,	Manchester.
Dalton, William Thomas,	Newcastle-on-Tyne.
Drury, Henry William Collins,	Doncaster.
Furness, Reginald Lester,	Salisbury, Rhodesia.
Harris, Stephen Edward,	Dublin.
Hollows, Arthur,	Northwich.
Humphrey, Frederick George.	Sevenoaks.
Jordan, Albert Edward,	Port Louis, Mauritius.
Kerr, William Scott,	London.
Langley, George,	Bedford.
McCallum, Edward Alfred,	Baku.
McLean, Alexander Malker,	Manchester.
Napier, Frederick Disney,	London.
Nichols, Henry John,	London.
Oliver, Arthur Richard,	Purfleet.
Parsons, Thomas George,	Dundee.
Reay, Edward,	Baku.
Robus, George Henry,	London.
Rosenthal, Frederick Michael Barbanel,	Gravesend.
Shoolbred, Andrew Reid,	London.
Turner, William Wallace,	Sydney.
Wallace, Cecil Percy,	London.
Watts, William John Thomas,	London.

GRADUATES.

Feeny, Cyril Joseph,	London.
Fletcher, Donald Corbet,	Doncaster.
Harris, Albert Edward,	London.
Kendall, Alfred Harold,	Great Yarmouth.
Manisty, Henry Scott,	London.
Priestley, Albert,	Halifax.
Pudsey, Fawcett,	Hull.
Thorne, Leonard,	London.
Thurston, Albert Peter,	London.
Warbrook, Frederick George,	Sheffield.

The PRESIDENT announced that the following three Transferences had been made by the Council since the last Meeting:—

Associate Members to Members.

BEGBIE, SYDNEY DAWSON, ...	London.
HARDCASTLE, EDWARD, ...	Bradford.

Associate to Associate Member.

WHITEHEAD, RICHARD DAVID, . . .	Derby.

The following Paper was read and partly discussed:—

"Sixth Report to the Alloys Research Committee: on the Heat Treatment of Steel"; by the late Sir WILLIAM C. ROBERTS-AUSTEN, K.C.B., D.C.L., D.Sc., F.R.S., *Honorary Member;* completed by Professor WILLIAM GOWLAND, *Member of the Committee.*

The Meeting terminated shortly before Ten o'clock. The attendance was 135 Members and 93 Visitors.

PROCEEDINGS.

29TH JANUARY 1904.

An EXTRA MEETING was held at the Institution on Friday, 29th January 1904, at Eight o'clock p.m.; T. HURRY RICHES, Esq., Vice-President, in the chair.

The Minutes of the previous Meeting were read and confirmed.

The Discussion on the Sixth Report to the Alloys Research Committee on "The Heat Treatment of Steel" was resumed and further adjourned.

The Meeting terminated at Ten o'clock. The attendance was 78 Members and 40 Visitors.

SIXTH REPORT* TO THE ALLOYS RESEARCH COMMITTEE: ON THE HEAT TREATMENT OF STEEL.

By the late Sir WILLIAM C. ROBERTS-AUSTEN, K.C.B., D.C.L., D.Sc., F.R.S., *Honorary Member*;
Completed by Professor WILLIAM GOWLAND, *Member of the Committee.*

Prefatory note by Professor Gowland.—On the death of my old friend, the late Professor Sir William C. Roberts-Austen, I undertook to complete, if necessary, for the Alloys Research Committee of the Institution, this Sixth Report on which he had been engaged for several years and the experimental work of which had been almost completed.

Ill-health and pressing official duties had long before his death prevented him from devoting as much time to the Report as he desired, so that the only manuscript he left for us was the introductory part which is contained in pages 8 to 15. This, with the exception of the sentences on page 8, beginning "His conclusions" and ending "carbon-iron system," is printed without alteration from that manuscript.

A careful search through Sir William's papers for notes or comments on the experimental work was unsuccessful, no traces of any being found. He had entrusted all the work relating to the heat treatment and photo-micrography of the steels to Mr. W. H. Merrett, Instructor in Assaying at the Royal School of Mines, then acting as his assistant, by whom it has been ably carried out on the lines he (Sir William) had laid down. The main body of the Report is hence based on Mr. Merrett's work, especially on his elaborate detailed notes of the experiments, and his excellent photo-micrographs, without which it could not have been written.

I have also to acknowledge my indebtedness to Mr. F. W. Harbord, of the Royal Indian Engineering College, for the determinations of the mechanical properties of most of the specimens after thermal treatment.

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* For the First, Second, Third, Fourth, and Fifth Reports, *see* Proceedings 1891, page 543; 1893, page 102; 1895, page 238; 1897, page 31; and 1899, page 35.

Introduction.—The Fifth Report to this Committee dealt mainly with the question of carburised iron considered from the point of view of the solution theory, and the conclusions which were reached rested mainly on the evidence afforded by the pyrometer and by the microscope as to the structure and grouping of different varieties of steel. In Plates 4 and 5 of that Report a complete equilibrium curve was given for carburised iron, and this has recently formed the basis of an elaborate study by Professor Bakhuis-Roozeboom,* of Amsterdam. [His conclusions, which are of great scientific interest, were obtained by applying the phase-doctrine of Gibbs to the study of the iron-carbon alloys. The chief reason for this inquiry was to determine the conditions of the existence of the phases of a system of one or more components. Iron and steel present a system of two components, iron and carbon, and by the phases of this system is understood all the distinct forms which may appear in the system. It is necessary in this system to consider the following phases: carbon and iron (which may exist in three phases, α, β, and γ); liquid and solid solution of carbon in γ (austenite) iron and cementite. Three phases are the maximum that may co-exist, according to the phase doctrine, in the case of stable equilibrium at one temperature and a constant pressure.

From his knowledge of the solidification and transformation of solid solutions Professor Bakhuis-Roozeboom was enabled to give a better correlation of the different parts of the iron-carbon equilibrium curve than was possible in the Fifth Report. The different fields shown in his curve give the limits of concentration and temperature for the most prominent of the phases that appear in the carbon-iron system.]

Since the writing of the last Report the value of the work to which the Institution has so unstintedly devoted its resources has received wide recognition. Whenever, in this series of Reports, the carburization of iron has been dealt with, the question of the allotropy of iron has assumed a prominent place. M. Osmond and the author have had to insist again and again upon the necessity for its acceptance, and it would have been scarcely necessary to refer to it now had not distinguished experimenters on the Continent recently based important conclusions on the views so long sustained. Reference has already been made to the work of Professor Bakhuis-Roozeboom; a communication * to the International Physical Congress, held at Paris in August 1900, affords another instance of much interest and significance. Professor Warburg, of the University of Berlin, appealed in this Paper to his colleague, Professor Van 't Hoff, and requested him to express his opinion respecting M. Osmond's views as to the transformation of carburised iron. In response, Van 't Hoff gave an authoritative statement † as to the vital importance of allotropy in relation to the properties of steel, which is as follows:—" β iron is capable of retaining variable quantities of carbon in the form of a homogeneous solid solution known as martensite, while this property is not possessed by the α modification of iron." This is a view which has long been advocated by M. Osmond and the author in the Reports presented to this Institution, and it is interesting to find that it is shared by such eminent authorities on molecular physics as Van t' Hoff and Professor Bakhuis-Roozeboom, and fortified by the adherence of such an excellent technical worker as Professor E. Heyn ‡, of the Imperial Laboratory at Charlottenburg. What is known as the allotropic theory has formed the basis of the thirteen years' work of the Alloys Research Committee, and its acceptance would alone have justified the labour which has been spent upon it.

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* Zeitschrift für Physikalische Chemie, xxxiv, 4, 1900, page 437.

It is now known that allotropic changes in the iron itself are the all-important factors in determining the relations between iron and carbon, which are involved in the characteristic capacity of steel for being hardened and tempered. If iron had existed only in the α form, it could never have been hardened by quenching; on the other hand, if β and γ iron were alone known, steel could never have been

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* Sur l'Hysteresis. Rapports Congrès International de Physique, Vol. ii, 1900, page 509. Paris (Gauthier Villars).

† *Ibid*, page 532.

‡ Stahl und Eisen, 1899, Nos 1 and 16.

tempered or annealed. The prevalent belief, therefore, of nearly two centuries, which claimed attention for the carbon alone, has had to be abandoned. Bergman, in 1781, held the first links of evidence which have led to the present conclusion, while Osmond, in the last decade, has forged the strong and important portion of the chain which we securely hold. In the future it will be realised how much the Institution of Mechanical Engineers has done to confirm, strengthen and diffuse the knowledge we possess on the important industrial question of hardening steel.

Annealing.—It will be well, in this concluding Report of the series, to deal with the operation of annealing, the importance of which is widely recognised, though the nature of the change it effects was, until recently, but little understood. The physical result is definite enough, as, by annealing, the elastic limit * of cast steel is, to cite only two constants, lowered from 18 tons per square inch to about 11, while the elongation is increased from 7 to 25 per cent. The influence of annealing, therefore, on the properties of the finished product is very great. "There seems," as Professor Sauveur has so well pointed out†, "to be considerable difference of opinion with regard to the meaning of the term 'annealing,' and still more concerning the proper temperature to which the metal should be heated, and the conditions which should prevail during the operation. To some steel-workers annealing conveys the idea of mere heating to a temperature sometimes considerably below, sometimes considerably above, the point known as Brinell's W (say 700 ± 25). To others it implies a prolonged heating at a temperature varying from a barely red to a very bright red or even a yellow heat. Some workers cool their steel very slowly in the annealing furnace; some more rapidly in the air; others, again, quench the metal after reheating to a dull red heat. Finally, the metal is heated in boxes or pipes, with or without packing material, or it is heated in the open furnace without any protection." The question then arises: Are the effects of tempering and annealing essentially of the same order? In attempting to answer this question, reference should be made to the lecture which was delivered by the author in 1889, before the British Association.* It was then pointed out that the effect of annealing and tempering was very complicated, and it was stated that Barus and Strouhal considered that annealing was demonstrably accompanied by chemical change, even at temperatures slightly above the mean atmospheric temperature, and that the "molecular configuration of glass-hard steel is always in a state of incipient change, ... a part of which change must be of a permanent kind." Barus, † however, said, "that during the small interval of time within which appreciable annealing occurs, a glass-hard steel rod suddenly heated to 300° C. (572° F.) is almost a viscous fluid," and he considers that glass-hard steel is constantly being spontaneously "tempered" at the ordinary temperature, which, he says, "acting on freshly quenched [that is, hardened] steel for a period of years, produces a diminution of hardness about equal to that of 100° C. (212° F.), acting for a period of hours." ‡ The nature of the molecular change is well indicated in the long series of researches which led them to the conclusion that in steel "there is a limited interchange of atoms between molecules under stress, which must be a property common to solids, if, according to Maxwell's conception, solids are made up of configurations in all degrees of molecular stability." Barus and Strouhal attach, relatively, but little importance to the change in the relations between the carbon and the iron during the tempering and annealing of hard steel. They consider that in hardening steel the "strain once applied to steel is locked up in the metal in virtue of its viscosity"; tempering is the release of this molecular strain by heat.

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* The term "elastic limit" is used in this Report in the sense of the "yield point."

† Journal, Iron and Steel Institute, 1899, II, page 200.

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* "Nature," 7 and 14 Nov., 1889.

† Philosophical Magazine, xxvi, 1888, page 209.

‡ That a very appreciable change in the structure of glass-hard steel occurs when it is reheated to 100° C. (212° F.) for some considerable time was confirmed microscopically, in 1899, by Sir W. Roberts-Austen, who quenched a piece of steel containing 0·4 per cent. carbon in mercury, and subsequently allowed it to remain for 1,500 hours at 100° C. On Figs. 157 and 158, Plate 39, are shown respectively the steel as quenched and after annealing. It will be seen that the original well-defined martensite has been transformed by this treatment into granular pearlite of a similar nature to that obtained in a hardened steel which has been tempered to straw colour under normal conditions.

If it were only a question of obliterating crystallization produced by undisturbed cooling of the metal from a temperature of about 725° C. (1,337° F.), then a very significant fact must be remembered. This is, that, in certain metallic masses which have become largely crystalline by slow cooling from the molten condition, the structure may be profoundly changed by heating to only 200° C. (392° F.). This was first noted, seven years ago, by M. Osmond and the author in the case of gold alloyed with 0·2 per cent. of antimony, which, from being coarsely crystalline as cast, becomes minutely crystalline when heated to only 200° C. (392° F.).* They pointed out that "bismuth, antimony, thallium, and aluminium, when present in gold in the proportion of about 0·2 per cent., behave in respect to gold in the same way as carbon does with regard to steel, but at a much lower temperature," and added that "the transformation of the structure of a metal, at a temperature so far below its melting point in the presence of only two-tenths per cent. of a foreign body, is probably not an isolated fact, and appears to open a new field for research." Other evidence of a similar kind is adduced in an Appendix † to this Report.

The simplest view of annealing has been presented with singular clearness by Sauveur, who states that the purpose of annealing "is to render the quenched metal as soft, tough, and ductile as possible, and to do so by decreasing the elastic limit and tensile strength only by such, so to speak, abnormal increments, as were acquired through hardening and cold working." The author has elsewhere defined "annealing" as heating above Brinell's point W, say, to 750° C.

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* Philosophical Transactions, Royal Society, vol. 187, 1896, page 431.

† "The Microscopical Examination of the Alloys of Copper and Tin," by Dr. W. Campbell, Proceedings 1901, page 1211.

(1,382° F.) followed by slow cooling, while "tempering" is heating to a point below W, with subsequent slow or rapid cooling, and has no useful effect except after quenching or cold working. This definition has been accepted by the French Commission on methods of testing.*

As a starting point for the enquiry, it may be accepted that maintenance of the steel, for a certain time, at a temperature between 625° C. (1,157° F.) and 750° C. (1,382° F.) is necessary. The present Report will, therefore, deal, to some extent, with the effect of annealing on different varieties of steel, the author having been assured that the investigation of this question would certainly yield results of industrial importance. It has long been known that the resistance of metals and alloys to mechanical stress varies considerably with the temperature at which the tests are conducted. In the operation known as annealing, the metal or alloy is raised to a somewhat elevated temperature, and this is followed by more or less prolonged cooling. The effect of this treatment is ascertained at the ordinary temperature, which, for industrial purposes, is practically a constant one, as the extreme variations do not differ by more than a few degrees. The results obtained, therefore, will depend on the complex thermal treatment the metal has previously undergone. The properties of a metal which has been annealed will thus be widely different from those which the same metal would be found to possess, if it were tested at any definite temperature within the range used in the operation of annealing. The conclusions which have been arrived at as to the properties of steel and other alloys, when tested within a more or less wide range of temperatures, will be found in an admirable report by Professor Ledebur, of Freiberg, which was translated into French by the late Professor Jordan, and to his work the reader should refer.†

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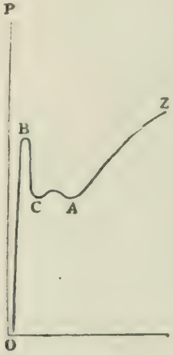
* *See* F. Osmond's correspondence on Sauveur's Paper, "The Relation between the Structure of Steel and its Thermal and Mechanical Treatment," Journal, Iron and Steel Institute, 1899, II, page 219.

† Jordan. Bulletin de la Société d'Encouragement pour l'Industrie Nationale, Aug. 1899, page 1157.

Before proceeding further, it may be well to point out that the autographic diagram of the "yield point" of annealed and unannealed steel is widely different, as has been shown by MM. Charbonnier and Galey-Aché * in a Paper entitled "Etude sur les Propriétés Physiques et Mécaniques des Métaux." They have clearly demonstrated that the form of an autographic stress-strain diagram, traced in testing the tenacity of a sample of iron or of steel, has a singular relation to the effect of annealing. Thus, it has long been known that there is a peculiar bend in the curve which marks the point at which the limit of elasticity is reached, and the metal begins to break down. If this curve be traced by a sensitive appliance, the critical portion of the stress-strain diagram is found to have the form indicated in the accompanying sketch, Fig. 1, in which the portion O B is within the elastic limit of the material, while B C A indicates variations in the resistance of the test-piece when the limit of elasticity is passed. A Z represents the permanent and regular elongation when the test-piece is submitted to an increasing load. The authors observe, however, that the portion B C represents false equilibrium, analogous to the physical phenomena known as "surfusion" and "supersaturation," and that the point C marks the true yield point. In the experiments cited by the authors the iron employed possessed a high degree of purity.

FIG. 1.



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* Communication to the Congress on Testing Materials.

It contained :—

Carbon	0·01
Phosphorus	0·01
Silicon	0·02

The diagram, Fig. 1, shows the curve recorded in testing this iron after it had been heated to 1,000° C. (1,832° F.) and slowly cooled.

The object of the experimental work, which will now be described, was mainly to observe and record the change in properties which different varieties of steel undergo, when submitted to thermal treatment. The particular variety of steel selected was made at Sheffield, and was very pure. In no case does the manganese exceed 0·25 per cent., and it is generally less than 0·20 per cent. The steel, as received, was in the form of three-quarter inch rolled bars, and was turned up into test-pieces of the dimensions given in the appended sketch, Fig. 2 * (page 16).

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* It will be noted that test-pieces of approximately this size have since been adopted by "Committee No. 1 of the American Section of the International Association for Testing Materials," whose recommendations were presented in the form of a Paper to the "International Congress on Methods of Testing Materials of Construction" at Paris, July 1900. The standard-turned test-piece advocated by this Committee for steel castings, axles, forgings, and tires, has a diameter of half an inch and a gauged length of 2 inches; the other dimensions are shown in the accompanying sketch, Fig. 3 (page 16).

In the manufacture of ordnance the test-bars taken from the hardened and annealed forging are now also small, each bar being 4½ inches long, and having in the central portion a cylindrical operative part 2 inches long and 0·533 inch in diameter. The enlarged ends are made to suit the holders of the testing machine, and the operative part is provided with two gauge points accurately adjusted 2 inches apart. It is imperative that the test-pieces should be of uniform dimensions, especially as regards length, since a short piece will elongate much more in relation to its original length than a longer one of the same material, the reason being that the chief part of the total elongation occurs where the specimen "necks" at the point of rupture, and, as the total elongation of the long specimen is not much greater than that of the short one, its elongation per cent. of original length is less.

FIG. 2.

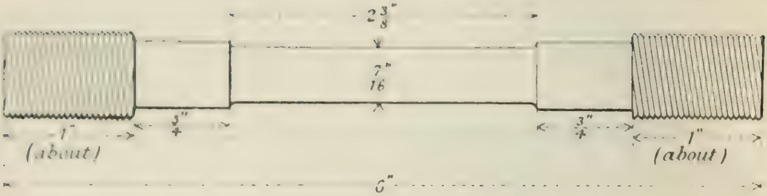
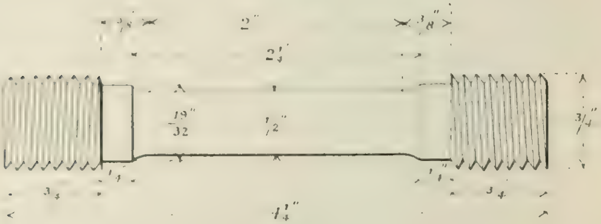


FIG. 3.



Eight series of bars were supplied for these experiments. The composition of these bars was as follows :—

Analyses of the bars by Mr. F. W. Harbord, Royal Indian Engineering College.

	A	B	C	D	E	F	G	H
Carbon . .	0·130	0·180	0·254	0·468	0·722	0·871	0·947	1·306
Silicon . .	0·020	0·024	0·033	0·072	0·098	0·080	0·081	0·050
Sulphur .	0·020	0·020	0·020	0·025	0·020	0·019	0·019	0·017
Phosphorus	0·011	0·022	0·025	0·016	0·015	0·019	0·013	0·015
Manganese.	0·185	0·250	0·190	0·160	0·217	0·190	0·181	0·180
Arsenic .	0·024	0·007	0·007	0·007	0·007	0·010	0·003	0·003

Tests were made on the different sets of bars as received, and after they had been subjected, respectively, to the following treatment. This grouping may therefore be adopted :—

(1) As received.

(2) Annealed for half-an-hour at the following temperatures: 620° C. (1,148° F.), 720° C. (1,328° F.), 800° C. (1,472° F.), 900° C. (1,652° F.), 1,100° C. (2,012° F.).

An attempt was made to keep the last set of bars at 1,200° C. (2,192° F.), during the annealing, but this was found to be impossible in the muffle used for this experiment.

The bars were packed in lime in ¾-inch wrought-iron tubes, closed at each end by screwed iron caps. These tubes were then packed in a large wrought-iron tube, the ends of which were covered with wrought-iron plates. This was placed in a closed gas-muffle, and a record of the temperature was taken by means of two thermo-couples attached to an autographic recorder. A diagram, showing the manner in which tubes were packed and placed in the muffle, and the arrangement of the thermo-couples, is given on Plate 2.

(3) Soaked for twelve hours at approximately the temperatures given in (2). (It being, however, found possible to maintain the soaking temperature at 1,200° C. (2,192° F.), in the case of the last set of bars treated, they were kept at this temperature, in preference to 1,100° C. (2,012° F.).) The bars were packed in iron tubes in the same manner as in the preceding group.

(4) Quenched at the following temperatures in water:—720° C (1,328° F.), 800° C. (1,472° F.), 900° C. (1,652° F.), 1,200° C. (2,192° F.).

(5) Quenched in oil.

In these experiments the bars were subjected to the following treatment:—

(*a*) Quenched at 720° C. (1,328° F.) and not reheated.

(*b*) Quenched at 720° C. (1,328° F.), 870° C. (1,598° F.) and 1,000° C. (1,832° F.), and reheated to 350° C. (662° F.).

(*c*) Quenched at 800° C. (1,472° F.) and 900° C. (1,652° F.), and reheated to 600° C. (1,112° F.).

The rate of cooling of the bars was in all cases taken by means of thermo-couples connected with the autographic recorder of the pyrometer, and this had the great advantage of showing, by an actual curve, the rate and degree of regularity with which the cooling proceeded. The maximum time of heating was twelve hours In dealing with such comparatively small bars, much does not appear to be gained by prolonging the cooling beyond this time.

It will be seen that great care has been taken to avoid annealing the different varieties of steel at a single temperature only. The temperature of annealing has been varied so as to ascertain its influence on steel with different degrees of carburization. Thus, one complete set of steel bars was annealed at 620° C. (1,148° F.), and others were respectively annealed at the following temperatures:—720° C. (1,328° F.), 800° C. (1,472° F.), 900° C. (1,652° F.), and 1,100° C. (2,012° F.). The influence of these varying temperatures on steel containing 0·13 per cent. of carbon can thus be compared with the effect on that containing as much as 1·3 per cent. It is interesting to note that when heated up to 800° C. (1,472° F.), steel with less than 0·468 per cent. of carbon does not appear to be affected, but with higher grades of carburization the ductility and reduction of area on fracture are changed.

The effect of heating crucible steels (containing 1·0 per cent. of carbon) to various temperatures, followed by slow cooling, has already been studied.* The effect on cast steel produced by heating it to a single definite temperature, followed by slow cooling, has recently also formed the subject of some careful experiments.†

Rolled steel, which was the material chosen for the experiments about to be described, has, of course, relatively higher importance on account of its wide use for constructional purposes.

For the purposes of this Report, each test-piece, after receiving its thermal treatment, had a portion of one of its ends removed for examination under the microscope. The bars were then mechanically tested for:—(1) Breaking strain; (2) elastic limit; (3) elongation; and (4) reduction of area.

The majority of the mechanical tests for this Report were made by Mr. F. W. Harbord, of the Royal Indian Engineering College, but those given in Tables 9, 10, 19 and 20 (also plotted in Figs. 16, 17, 26 and 27 respectively) were carried out by Mr. E. G. Ll. Roberts at the Finsbury Technical College.

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* G. W. Sargent. Trans. Amer. Inst. Mining Engineers, February 1901.

† J. O. Arnold. Journal, Iron and Steel Inst., 1901, I, page 191.

Sections were also taken from the original bars, about ¾ inch in diameter and ⅜ inch thick, and were thermally treated under identically the same conditions as the bars, the object being to determine the extent and nature of the differences in structure of these small pieces, and of the sections removed from the bars after thermal treatment. It was found however that there was really very little difference in structure between the two classes of sections except, perhaps, that, in the case of quenching in water, the abstraction of heat from the bars had not been so rapid as in the small sections, and the martensite in the latter cases was more sharply developed. The quenched specimens of the high carbon steel were cut by means of a circular disc of mild steel attached to a lathe, diamantine or emery being used as the "cutting" agent in the same way that diamond dust is used with a lapidary's wheel.

As the methods by which the photo-micrographs were prepared for this Report differ in detail from those generally practised, it will not be out of place at this point to describe briefly the apparatus used and the methods employed in preparing specimens of steel for microscopic examination.

Methods used for preparing Photo-micrographs.—The actual polishing of the specimens for microscopic examination was carried out generally in accordance with the methods laid down by M. Osmond,* although later the modifications suggested by Professor H. le Chatelier † were adopted. These modifications somewhat reduced the labour of polishing. The polishing powders employed consisted of alumina, in various states of division, prepared from ammonia alum. The ammonia alum was first very thoroughly calcined, and the product treated with water containing 0·1 per cent. of nitric acid. The mixture was next stirred occasionally for several hours and then allowed to settle. Although the settlement of the alumina is rapid in the acid solution, it nevertheless takes a long time to separate if the solution is made neutral, and, occasionally, when this is ammoniacal, as long as ten or twelve days are necessary for complete settlement. The powder was then washed several times with distilled water, by decantation, until the particles would no longer settle quickly. Two cubic centimètres of ammonia were added to each litre of water and decantation was resorted to at intervals of fifteen minutes, one hour, four hours, twenty-four hours and eight days, and the respective powders collected separately. These were mixed in each case with scrapings of very dry castile soap in the proportion of one part of soap to ten parts of wet powder. The mixture was then melted in a water-bath, stirred thoroughly, and poured into tin tubes similar to those used for holding artists' oil-colours.

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* F. Osmond. "Bulletin de la Société d'Encouragement pour l'Industrie Nationale," 4ᵉ Série, May 1895, vol. x, page 480.

† *See* Prof. H. le Chatelier's Paper in the "Bulletin de la Société d'Encouragement pour l'Industrie Nationale," 5ᵉ Série, Sept. 1900, vol. vi, page 365.

The polishing machines used for the latter part of this research were made in the Metallurgical Laboratory of the Royal School of Mines. The machine employed for the rough polishing, as will be seen from Fig. 4, Plate 1, consists of an arrangement not unlike a lathe-head with a mandril at each end, one of which is "screwed" to a right-handed and the other to a left-handed thread. A number of wooden discs about 12 inches in diameter are attached to chucks which fit the mandrils, the faces of the discs being covered with commercial emery papers of different degrees of fineness. The machine is mechanically driven at about 200 revolutions per minute. It is fitted with broad hand-rests similar to those used on an ordinary pattern-maker's lathe. With this arrangement two operators can work at the same time, and, by polishing the specimens lightly, the overheating complained of by many workers is avoided. With the aid of this machine it is possible, by using the finer grades of commercial emery papers (notably those prepared by Hubert), to obtain specimens sufficiently well polished for eye observation and low-power work; the character of the results may, however, be greatly improved by rubbing the finest of Hubert's papers (number 0000) with a piece of hard steel and a little oil before use.

The polishing machine used for fine work, shown on Fig. 5, Plate 1, is an elaborate modification of the one used by M. Osmond. It consists essentially of two vertical spindles, which are drilled to receive a series of cast-iron discs about 12 inches in diameter. Each disc is covered with ribless cloth, which is secured in position by means of a gun-metal ring. The discs rotate within two boxes fitted with sliding glass lids, and the motive power is obtained from a small electric motor which is attached to a "fast and loose" pulley, so that it is not necessary to switch off the motor every time it is desired to stop the discs. This machine is exclusively used for the Le Chatelier powders and washed rouge, a separate disc being kept for each polishing powder. The discs, which are kept moist with water, rotate about 400 times per minute.

The camera used for the photographic work was of the horizontal type and about 6 feet long. About two-thirds of its length was made up of collapsible bellows, whilst the other third consisted of a light conical tube which tapered towards the microscope. The other end of this tube was so hinged that the tube could be diverted horizontally, when it was necessary to use the microscope alone. A focussing rod was fixed to the side of the camera, and this actuated the fine adjustment by means of a thin catgut band and pulley, so that the operator could focus the image on the ground-glass screen with the greatest possible ease. In certain cases it was found that the light reflected from the object was not sufficient to give an image on the ground-glass screen and that focussing was not possible; this difficulty was eventually overcome by affixing five cover glasses to the ground glass—one in the middle and one at each corner—by means of Canada balsam. The spaces covered by the glasses being transparent, it was possible to place a small microscope over them and then focus the image by turning the fine adjustment, as if the whole camera were a microscope, and the small subsidiary microscope an eye-piece.

The microscope, which was made by Baker, was fitted on a cast-iron turntable, so that a small amount of traverse to the right or left could be obtained when necessary. The magnifications which were found to be most useful were 50, 140, 850 and 1,600 diameters.

When using a 6-foot camera at full length, and a low-power Zeiss projection eye-piece, these magnifications may be obtained with the Zeiss 35 mm. projection, the 24 mm., the 4 mm. with correcting collar, and the 2 mm. immersion objectives respectively. The projection lens is, of course, used without an eye-piece. All the high-power eye-pieces used at the Mint were unsatisfactory as regards definition; and it was found to be better to obtain greater magnification by means of a long camera than by employing high-power projection eye-pieces.

The illumination was obtained by means of a small hand-fed arc lamp, which was replaced later by a "Brush" automatic lamp working at an angle of 25° to the vertical. It is essential that the top carbon should be the positive one, and that the crater formed should be small and in such a position that the light is thrown towards the microscope. Such an arc should "burn" about 10 ampères.

Since the specimens were opaque, it was necessary to illuminate them from above, and this was generally done vertically by means of a Beck's vertical illuminator; this is a small disc of cover-glass, which, placed at an angle of 45° in the optic axis of the microscope, receives the light from an aperture in the side of the apparatus, and reflects it upon the objective; the lenses then concentrate the light upon the object. A small prism devised for vertical illumination by Nachet, of Paris, was occasionally used with very good results, especially when it was necessary to economise light.

For ordinary work, no water-jacket was placed between the arc light and the microscope, but a hole $\frac{3}{4}$-inch in diameter was drilled in the brass tube of the Beck's illuminator on the side opposite that at which the light enters, so that the light which is not reflected by the glass in the illuminator will pass out through this opening and with it some of the radiant heat. It is a curious fact that most of the heat passes through the glass and but little is reflected through the objective. For some work the filament of an incandescent electric lamp was employed, this being placed close to the slit of a Nachet vertical illuminator. For this purpose it is necessary to use a very low voltage lamp, say 2–6 volts, as a filament requiring a greater electrical pressure than this is too thin for illuminating the whole of field.

The specimens of steel, after being thoroughly polished by the aid of emery and rouge papers, or by means of the pastes of soap and alumina powder, were lightly rubbed during the time required for about two thousand revolutions on a wet wheel, upon which a trace of washed rouge had been placed. At this stage the specimens become lightly engraved, the harder constituents appearing in relief; and should be, of course, quite free from scratches.

The structure of the specimens, in most cases, is not shown by polishing only, but must be made evident by physical or chemical processes which produce different effects upon different constituents of the steel. For the purposes of this Report, the constituents were usually brought out clearly, either (1) by rubbing the specimen with liquorice juice on parchment; (2) by rubbing the specimen with a 2 per cent. solution of ammonium nitrate on parchment; or (3) by attacking it with a very dilute solution (1 per cent.) of nitric acid in alcohol. After rubbing on parchment with liquorice juice or ammonium nitrate, it is necessary to rinse the specimen first in water, at the same time gently rubbing the surface with the fingers, and then to immerse it in alcohol. After remaining in the alcohol for a minute or two, the specimen is lightly rubbed with a chamois leather which has been dipped in benzene. Specimens which have been treated with an alcoholic solution of nitric acid should be rinsed immediately in alcohol, and then be rubbed with the chamois leather dipped in benzene. The time necessary for the attack varies with the carburization and the previous thermal treatment of the steel. With the solution of nitric acid in alcohol the time varies from thirty seconds to two minutes, a dead soft, low carbon steel taking thirty seconds, and a quenched 0·8 per cent. carbon steel about two minutes.

The specimens were mounted on ordinary glass slides with a wax composed of resin, beeswax, red ochre, and plaster of Paris. No special apparatus was used for levelling the specimens on the glass slips, as it was found possible to work more rapidly and quite as accurately without these appliances. When a specimen was slightly "out of truth" under the microscope, it was adjusted by means of the levelling stage. The red wax, mentioned above, was found to be the best possible material for the purpose of mounting, as it remains plastic for a sufficiently long time to allow the specimen to be levelled by hand, and then "sets" quite hard. The majority of the photo-micrographs taken for this Report are of a magnification of 1,600 diameters, as only with such a high magnification as this can the actual condition of the iron carbide, in a slowly cooled steel, be seen. All steels which have been quenched must, of course, be examined under a high power. A small electro-magnet attached to the stage of the microscope was found to be very useful for examining specimens when the faces had been properly "trued."

ANNEALING EXPERIMENTS.

The Effects of Annealing.—The effects of annealing on the mechanical properties and microstructure of the steel bars as revealed by the new experiments will now be discussed. Table 1, the results of which were obtained at the Royal School of Mines and are plotted in Fig. 8, Plate 4, shows the breaking strain, elongation, and reduction of area of the rolled bars as received:—

TABLE 1.

(*From the Rolls.*)

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	30·22	20·00	34·73
0·180	31·52	12·50	29·71
0·254	33·25	12·70	25·31
0·468	36·96	6·25 *	18·76
0·722	49·00	11·72	3·43
0·871	58·02	5·47	5·38
0·947	53·74	7·03	5·63
1·306	56·11	7·03	8·48

* Abnormal.

It will at once be noticed that both the reduction of area and the elongation are extremely low in all the specimens, whereas the breaking strain is about normal. This led to the belief that the bars had been submitted to "cold-rolling," that is, that they had been rolled after the separation of the constituents of the steel. Sections were therefore taken from the bars, both at right angles and parallel to their axes, but in no case could evidence of cold rolling be detected. A photo-micrograph, prepared from each of the transverse sections, is shown on Plate 17, from which it is evident that, although no "cold rolling" has taken place, the bars have been rapidly cooled near the critical point Ar_1, and that some sorbite has been produced in nearly every case. This would, to a certain extent, account for the very low reductions of area and elongation of the bars.

For the sake of convenient comparison the results of the mechanical tests of each series of bars dealt with in this research are plotted on Plates 4 to 16 inclusive.

Annealing Bars at 620° C. (1,148° F.) *for Half-an-hour.*—It has been frequently stated by metallurgists that practically no change is brought about in the mechanical properties of slowly-cooled iron and steel when heated to temperature below the A_1 point (about 680° C. (1,256° F.)) and allowed to cool naturally.

In this experiment great care was taken that the temperature at no time reached the point at which the A_1 change occurs. The bars required about half-an-hour to attain a uniform temperature of 620° C. (1,148° F.) They were then kept at this temperature for half-an-hour, when the gas was turned off and they were allowed to cool slowly in the muffle.

Since the annealing temperature is well below the A_1 point, it is evident that any change that may have taken place in the mechanical properties cannot be due to the solution of the carbide of iron and its subsequent separation. Table 2 (page 26) contains the results of the mechanical tests of this series of bars. They are also plotted in Fig. 9, Plate 4.

TABLE 2.

Bars annealed at 620° *C.* (1,148° *F.*) *for Half-an-hour.*

(“*Normalised*” *Bars.*)

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	No Tests.	—	—	—
0·180	30·60	26·50	33·00	62·85
0·254	34·50	27·78	24·00	55·06
0·468	37·02	27·36	24·00	49·70
0·722	50·22	31·68	20·50	33·48
0·871	55·02	29·28	12·00	22·11
0·947	52·90	34·20	15·00	27·00
*1·306	51·54	40·92	3·00	3·90

* Broke outside gauge points.

It will be seen that the mechanical properties of these annealed bars differ considerably from those of the bars as received from the rolls. There is little difference in the breaking strains up to 0·722 per cent. of carbon, but beyond this point to 1·306 per cent. of carbon the untreated bars are the stronger. There is, however, a well-marked difference in the cases of the elongation and the reduction in area of the bars containing up to 0·947 per cent. of carbon. From these results it is evident that the changes which have been produced in the 0·180, 0·254, 0·468, and the 0·722 per cent. carbon bars by annealing at 620° C. have mainly occurred in the ferrite, since the bars containing most of this constituent show the greatest increase in both elongation and reduction of area. The rolled bars had doubtless been “worked” after some of the ferrite crystals had formed, and, in this way, slip-planes were produced. These planes being more or less parallel to the axis of the bars were not sufficient to affect materially the breaking strain, but they nevertheless tended to reduce greatly the elongation and reduction of area in the original bars. By the subsequent annealing of these bars to 620° C. (1,148° F.) the slip planes became coherent, and a greatly increased elongation and reduction of area resulted. It will also be noticed that an increase in the elongation and reduction of area also occurs in the 0·871 and the 0·947 bars, but to a less extent than in the previous cases. This is doubtless due to the annealing at 620° C. effecting a better coherence between the ferrite and cementite laminae in the pearlite of the bars. Since cementite itself is not a plastic body, "slip" cannot easily take place in it; hence it is impossible to improve greatly the elongation and contraction of area of steels containing much cementite, by annealing at temperatures below 680° C. (1,256° F.).

Further, as sorbite is transformed more or less into pearlite at a temperature far below the A_1 point, it is possible that the plasticity of the bars has been aided by this partial transformation. Reference to the photo-micrographs on Plate 18 will however show that the duration and temperature of this annealing has not been sufficient to bring about this change completely.

It will be seen, on reference to Table 2, and Fig. 9, Plate 4, that the limit of elasticity compared with the breaking strain is abnormally high throughout this series of bars. As the elongation and reduction of area are satisfactory, it is possible that the annealing of worked bars at temperatures immediately below A_1 may have some commercial significance.

These results are at variance with the work of many investigators, but they are borne out by Brinell * and Axel Wahlberg of Stockholm, who showed that iron and steel, especially if cold wrought, will, if heated up to a blue annealing temperature, increase in toughness, and, in certain exceptional cases, also in tenacity. The elastic properties will be enhanced and the quality of the material will be improved in most respects. Brinell found that by heating a series of steels, containing from 0·09 to 0·84 per cent. of carbon to 350° C. (662° F.), "the respective values obtained for ultimate stress show that the

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* Journal, Iron and Steel Institute, 1901, II. pp. 234–255.

absolute strength is not very much altered in consequence of this treatment, but that the elasticity of the material is considerably increased."

Bauschinger * holds that any heating below 450° C. (842° F.) would, in general, prove to be ineffective in the case of ingot metals; whilst Ledebur † states in his book that any heating up to temperatures below 500° C. (932° F.) would prove to have no influence on cold wrought material.

From the results of the authors' experiments, it would seem that there is every reason to believe that both the elongation and reduction of area in worked bars are greatly increased by annealing at even these low temperatures, provided the bars are kept at these temperatures for a sufficient length of time to allow the slip-planes and the pearlite laminae to cohere.

It is interesting to note that the maximum breaking strain occurs in the 0·871 per cent. carbon bar in both the annealed and unannealed steel, and also that there is a sudden drop in the elastic limit in the annealed bar at this point. Similar properties have been found to occur in the eutectics of most double alloys, notably those of the copper-silver and the lead-tin series; and it shows that the intimate mechanical mixture of a eutectic is not conducive to a high limit of elasticity.

The lowering of the breaking strain by annealing in the cases of the bars containing 0·871, 0·947 and 1·306 per cent. of carbon has been brought about by the partial transformation of the sorbite present into pearlite.

Annealing bars at 720° C. (1,328° F.) *for Half-an-hour.*—On reference to the equilibrium curve of carburised iron, given Fig. 7, Plate 3 (which is the curve published in the Fifth Report to the Alloys Research Committee, modified in accordance with recent work), it will be seen that the effect of this annealing is, in the first place, the solution of the constituents of the pearlite in one another, and, in the low carbon steels, a further partial solution of the ferrite grains. The temperature of 720° C. (1,328° F.) was chosen for this annealing, that being midway between the A_1 point and the chief magnetic change point A_2.

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* Mittheilungen aus dem mechanischtechnischen Laboratorium in München, Part xiii, page 26.

† Handbuch der Eisenhüttenkunde, 3rd edit., page 712.

The conditions of cooling were the same as for the annealing at 620° C. (1,148° F.). An autographic record showed that the Ar_1 change extended over a range of, approximately, ten minutes. As the bars were allowed to cool slowly in the muffle, the conditions were perfectly favourable for the complete separation of the constituents of the steel.

The mechanical results yielded by these bars are given in Table 3, and are also plotted in Fig. 10, Plate 5:—

TABLE 3.

Bars annealed at 720° *C.* (1,328° *F.*) *for Half-an-hour.*

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	20·16	11·34	44·50	73·26
0·180	26·52	14·52	36·00	72·54
0·254	28·80	18·24	32·50	62·66
0·468	32·82	21·60	29·00	58·56
0·722	39·96	22·98	23·00	47·88
0·871	43·98	*	20·00	40·42
0·947	39·30	*	22·00	45·00
1·306	50·58	*	7·00	5·12

* No definite yield point.

If we compare these results with those of Table 2 (page 26), bars annealed at 620° C. (1,148° F.), it is evident that the general result of this treatment has been to increase greatly the elongation and reduction of area, while the breaking strain has been considerably reduced in every case.

The elastic limit, which could, however, only be determined in the bars containing from 0·130 to 0·722 per cent. of carbon, owing to there being no indication on the stress-strain curve, is low. The bar containing 1·306 per cent. of carbon, if compared with the corresponding bar in Table 2, will be found to have practically the same breaking strain, but its elongation and reduction of area, although low, are higher.

The explanation of these changes in mechanical properties is not difficult to find; the steels have been heated to a temperature which is only slightly above the Ac_1 point, and the cooling down has been so regulated that the Ar_1 change required ten minutes for its completion. In the photo-micrographs shown on Plate 19 it is evident that, under these circumstances, the iron carbide has separated, in the low carbon steels (0·130 and 0·180 per cent. carbon) not in the form of pearlite, but as massive cementite. In the steels containing from 0·254 to 0·947 per cent. of carbon this massive cementite does not, however, occur, but the pearlite layers are much larger than in the rolled bars and also than in those annealed at 620° C. (1,148° F.).

Since this series of bars has been kept at a temperature which is but a few degrees above the A_1 point, the effect of the annealing is practically the same as a very slow cooling through this point would be. The coherence of the cleavage planes in the ferrite has been more complete than in the 620° C. (1,148° F.) annealing; hence the greater elongation and reduction of area; and, at the same time, the annealing, or what really amounts to a very slow cooling at Ar_1, has caused the iron carbide to separate, either massive or in large flakes, hence the lowering of the breaking strain and the elastic limit. The apparently anomalous strength of the 1·306 per cent. carbon bar is probably due to the fact that at 720° C. (1,328° F.) the eutectoid is practically unable to dissolve the cementite, and the pearlite thus retains a lamellar structure. Had the temperature been higher, as is shown in the next experiment, the cementite would have been dissolved, largely granular pearlite intermixed with cementite globules would have separated, and the strength would have decreased.

Axel Wahlberg,* in his Paper to the Iron and Steel Institute in 1901, advocates the annealing of steel required for structural purposes. He states that: "According to what seems to be the most commonly accepted opinion, any wrought material is rendered tougher by means of annealing and subsequent slow cooling, while, at the same time, the strength and elastic properties are reduced. From a general point of view this is no doubt perfectly true, and quite consistent with the structural changes occasioned by such a mode of treatment. It is a common saying with regard to such cases of annealing, that what is gained in tenacity is lost in strength and elasticity, and that it is only in the case of unwrought material, such as ingots and castings, that a general improvement of all the physical properties takes place in consequence of annealing with subsequent cooling, whether slow or sudden." Further that his results "by no means bear out this idea, but, on the contrary, most decidedly tend to disprove it. They show that, as a rule, a judicious annealing has effected a marked improvement in the tensile no less than in the ductile properties." He then gives experimental evidence showing that all classes of steel are improved in their mechanical properties by judicious annealing; he does not, however, take cognisance of the influence which the rate of cooling through the critical points, especially Ar_1, has on the character of the metal.

The next series of annealing will show how very great an influence the rate of cooling through the Ar_1 point has on the mechanical properties of steel.

Annealing bars at 800° C. (1,472° F.) *for Half-an-hour.*—In these experiments the bars were allowed to cool in the muffle as in the previous annealings, but the autographic record showed that the time occupied in passing the Ar_1 point only averaged about seven minutes, instead of ten as in the last case, the more rapid cooling through the Ar_1 point probably being due to the initial cooling from a higher temperature. Under these circumstances the exterior of the muffle rapidly cools, and by the time 680° C. (1,256° F.) is reached the heat radiates more quickly than when the muffle is cooled from 720° C. (1,328° F.).

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* Journal, Iron and Steel Institute, 1901, II, page 244.

Reference to the equilibrium curve of carburised iron on Fig. 7, Plate 3, will show that the temperature of this annealing is about 25° C. (45° F.) above the magnetic change point A_2. Annealing at this temperature will enable the pearlite constituents to dissolve in one another, and in the steels containing less than 0·8 per cent. of carbon considerably more ferrite will be dissolved than in the preceding experiment.

The mechanical properties of the bars are plotted in Fig. 11, Plate 5, and are also given in Table 4 :—

TABLE 4.

Bars annealed at 800° *C.* (1,472° *F.*) *for Half-an-hour.*

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	20·10	10·20	46·20	71·16
0·180	26·46	16·08	35·00	67·32
0·254	29·40	19·44	29·50	58·56
0·468	33·00	18·72	27·50	45·60
0·722	42·48	*	17·70	31·74
0·871	52·50	*	11·50	16·92
0·947	39·96	22·50	18·00	28·44
1·306	39·12	*	20·00	33·90

* No definite yield point.

It will be seen that the breaking strains of the 0·130, 0·180, 0·254 and 0·468 per cent. carbon bars are practically the same as in the last experiment, whilst the 0·722 and 0·871 bars are much stronger, the latter being markedly stronger than any other bar in the series now under consideration. In this connection it may be mentioned that its composition closely corresponds with the pure saturated steel of Arnold.

It is interesting to note that, while the breaking strain reaches a maximum at this point, yet, at the same time, the elongation and the reduction of area are the lowest of the series, the former being only 11·50 and the latter 16·92 per cent. Up to this point too, generally speaking, the elongation and the reduction of area are lower than in the bars annealed at 720° C. (1,328° F.), but beyond it there is a considerable increase in these properties.

Curiously enough the 1·3 per cent. carbon bar is much weaker than the corresponding bar annealed at 720° C. (1,328° F.). It will be remembered that there was a similar decrease in the breaking strain of the 0·947 per cent. carbon steel annealed at 720° C. (1,328° F.) as compared with that of the bar before treatment. An examination of the photo-micrograph of this steel, Fig. 50, Plate 19, will reveal the fact that the original pearlite no longer exists as such, but has been transformed into tiny, more or less rounded, masses of cementite. On examining the microstructure of the 1·306 per cent. carbon steel annealed at 800° C. (1,472° F.), Fig. 59, Plate 20, it will be seen that a similar change in the pearlite has taken place.

In order that this change may be brought about, it appears to be essential that some of the free cementite should be dissolved by the eutectoid, and that the rate of cooling of the metal should be slow. The lowering of the breaking strain of the 0·947 per cent. carbon bar at 720° C. (1,328° F.) is due to the fact that a steel with this percentage of carbon contains very little free cementite, and this is easily dissolved at that temperature. In the 1·306 per cent. carbon bar, however, the cementite being present in greater amount, a higher temperature is therefore necessary for its solution, so that the lowering of the breaking strain in this particular case does not occur until the steel is annealed at 800° C. (1,472° F.).

It is obvious that a mixture of massive cementite and globules of cementite embedded in a matrix of ferrite would not be so strong as the ordinary cementite and pearlite structure. An increased elongation and reduction of area would therefore be expected, and reference to Fig. 11, Plate 5, will show that this is actually the case.

Annealing Bars at 900° *C.* (1,652° *F.*) *for Half-an-hour.*—This annealing temperature was chosen because, at 900° C. (1,652° F.) (the A_3 point), the whole of the ferrite dissolves in the solid mother liquor to form a solid solution of carbon in iron, or, in other words, the last of the β iron is transformed into the γ state. Annealing for half an hour at this temperature will cause nearly all the constituents of the bars to dissolve completely in one another. During the subsequent cooling they will again separate, and the forms they will assume will depend, to a great extent, on the rate at which the steel is cooled. The conditions of cooling in this experiment were practically the same as in the last case, except, of course, that the initial point was 900° C. (1,652° F.) instead of 800° C. (1,472° F.). The results of the mechanical tests of the bars after annealing are plotted in Fig. 12, Plate 6, and are also given in Table 5 :—

TABLE 5.

Bars annealed at 900° *C.* (1,652° *F.*) *for Half-an-hour.*

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	21·48	13·02	45·00	71·16
0·180	27·84	15·84	33·50	60·24
0·254	29·46	17·28	32·50	54·84
0·468	32·46	18·03	28·00	46·26
0·722	43·20	*	16·50	25·86
0·871	50·40	*	11·20	15·84
0·947	51·12	*	10·00	15·42
† 1·306	44·52	*	5·50	5·58

* No definite yield point. † Broke at gauge points.

On comparing Table 5 with the preceding one, it is evident that this treatment has not materially altered the breaking strains in the bars containing up to 0·871 per cent. of carbon. Beyond this point, however, it has increased the strength of the steel considerably, the 0·947 and the 1·306 bars having, respectively, a breaking strain of 11·16 and 5·4 tons greater than the same bars annealed at 800° C. (1,472° F.). This indicates that it is essential, in order to obtain greater strength in bars of this content of carbon, that they should be annealed at a temperature at which the carbide is thoroughly dissolved; then, on cooling, the cementite and pearlite are entirely reformed. If such steels are annealed at too low a temperature the free cementite is not, or is only partially, dissolved, and, if partially dissolved, fresh grains are produced on cooling, thus giving a more minute structure and greater weakness. A similar instance will be shown later in the cases of soaking for 12 hours at 800° C. (1,472° F.) and 900° C. (1,652° F.). The 0·871 per cent. carbon bar has no longer the greatest breaking strain of the series, that containing 0·947 per cent. of carbon being slightly stronger. The elongation and reduction of area are also practically the same as in the 800° C. (1,472° F.) annealing in all the bars up to and including that containing 0·871 per cent. carbon; but the 0·947 and the 1·306 bars show a considerable reduction in these properties, the reduction being most marked in the latter, where extension has fallen from 20 to 5·5 per cent., and the contraction of area from 33·9 to 5·58 per cent.

The photo-micrographs of this series, which are given on Plate 21, indicate that segregation of the iron carbide has taken place in the 0·130, 0·180, 0·254 and the 0·468 per cent. carbon steels, and that but little pearlite exists in them. This is not, however, the case with the others; in the 0·722 and the 1·306 bars the carbon exists mainly as pearlite, whilst the latter has but little free cementite in its structure, and has evidently been partly "burnt" by the treatment, some of the free cementite having been decomposed into amorphous carbon and ferrite.

The 0·871 and the 0·947 carbon steels, which consist mainly of pearlite, have become much more minute in structure; in fact their whole mass is made up almost entirely of granular pearlite. It is probable that the increased strength of the 0·947 bar is due to a partial decomposition of the carbide setting free amorphous carbon; this has practically made it a saturated steel, and the loss of strength in the 0·871 bar (the originally saturated steel) is due to a similar cause. In order to determine what effect the duration of the annealing has on the structure of these grades of steel, a series of bars were heated to 900° C. (1,652° F.) for ten minutes only, and were allowed to cool under the same conditions as the bars annealed for half-an-hour at the same temperature. They were then examined microscopically and photographed, and the structures obtained are represented on Plate 22. It will there be seen that under these conditions the carbide has separated in quite a different manner from that in the bars annealed for half-an-hour. In the bars, up to and including the 0·871 steel, the pearlite has separated in well-defined laminæ; the 0·947 and the 1·306 steels have, however, developed a more or less granular pearlite. Unfortunately, mechanical tests were not taken of these bars, but one would predict from their structures that they would be very similar to those of the series annealed for half-an-hour at 800° C. (1,472° F.).*

This experiment proves that not only does the rate of cooling affect the structures, but that the time during which the bars are heated to a definite temperature has a considerable influence on their mechanical properties.

Annealing bars at 1,100° *C.* (2,012° *F.*) *for Half-an-hour.*—It will be seen, on reference to the carbon-iron equilibrum curve, Fig. 7, Plate 3, that this temperature is about 140° C. (252° F.) above the point at which the last portions of cementite pass into solid solution in the 1·306 per cent. carbon steel. Annealing for half-an-hour will thus cause the constituents of the steels to dissolve in one another completely, and to be retained for some time in this homogeneous state well above their solution points.

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* *See* Table 4 (page 32) and Plate 20.

The conditions of cooling were the same as in the previous annealings, but an autographic record showed that the average time for the Ar_1 change to take place completely was only about seven minutes. This was evidently partly due to the increased rate of cooling, resulting from the higher initial temperature, and also to the partial decomposition of the Fe_3C in some of the members of the series.

The mechanical properties of the bars are plotted in Fig. 13, Plate 6, and are also given in Table 6 :—

TABLE 6.

Bars annealed at 1,100° *C.* (2,012° *F.*) *for Half-an-hour.*

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	—	—	—	—
0·180	26·91	15·37	39·50	60·60
0·254	28·11	15·30	33·50	54·77
0·468	31·38	14·28	27·00	40·38
0·722	42·38	*	14·00	17·21
0·871	47·69	*	11·00	12·51
0·947	49·62	*	7·50	9·07
1·306	46·62	*	6·50	8·94

* No definite yield point.

On comparing these results with those yielded by the bars annealed at 900° C. (1,652° F.), Table 5 (page 34), it will be found that the differences in the breaking strains of the two series are not great, the greatest divergence being in the 0·871 per cent. carbon bars, which show a difference of 2·7 tons per square inch, that annealed at 1,100° C. (2,012° F.) being the weaker. It will be noticed that there is a tolerably close agreement as regards elongation in both sets of bars. As regards reduction of area, only those bars containing 0·180 and 0·254 per cent. of carbon are similar, the remaining bars of the series annealed at 1,100° C. (2,012° F.), with the exception of the 1·306 bar, being lower than those annealed at 900° C. (1,652° F.).

Since the mechanical properties of the bars annealed at 900° C. (1,652° F.) and 1,100° C. (2,012° F.) for half-an-hour are similar, one would expect to find their structures also much alike. Photo-micrographs of the latter series have been reproduced on Plate 23, and, although it will be seen that the structures of the 0·130, 0·180, 0·254, 0·468 and 0·722 steel correspond with those of the former, yet the three high-carbon steels are quite different, their structures indicating that they have been partially "burnt." This effect is even more marked under a lower magnification when the metal appears to be composed of a number of grains bounded by more or less straight lines, and exhibits a structure similar to that shown on Fig. 133, Plate 35. These burnt structures, under the high power (1,600 diameters), show a large amount of ferrite and also granular and massive cementite, from which it would appear that part of the iron carbide originally present has been decomposed into iron and amorphous carbon. To prove that this actually occurs, some Fe_3C was prepared by Abel's method * from low-carbon steel, and was packed in a tube into which a thermo-couple was introduced. A heating curve was then taken, with the usual precautions, to about 1,200° C. (2,192° F.), and it was found, on examining the record, that two change points had occurred at about 1,100° C. (2,012° F.). The residue was then examined, and found to contain free carbon.

SOAKING EXPERIMENTS.

Soakings.—Since a number of investigators have laid considerable stress on the length of time to which steel required for structural purposes should be annealed, and since ingots and forgings are, in practice, occasionally soaked for ten, twelve, or more hours, it was considered advisable to determine the mechanical properties of steel bars which had been heated to definite temperatures for twelve hours. The conditions of cooling in the following experiments were similar, in every way, to those in the experiments on annealing.

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* Proceedings, Institution of Mechanical Engineers, 1883, page 56.

The extent to which the changes in the mechanical properties are actually due to the long duration of the annealing can therefore be clearly shown. Although the rate of cooling through the critical points, Ar_1 especially, is of the utmost importance, it will nevertheless be seen that the duration of the annealing at a definite temperature has a very considerable influence on the mechanical properties of the bars. The bars in this series of experiments were, after soaking, turned into the form required for the test-pieces, so as to avoid errors from the oxidised surface.

Soaking Bars at 620° *C.* (1,148 *F.*) *for Twelve hours.*—The results of the mechanical tests of this set of bars are plotted in Fig. 14, Plate 7, and are also given in Table 7:—

TABLE 7.

Bars soaked at 620° *C.* (1,148° *F.*) *for Twelve Hours.*

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	19·75	10·64	48·50	81·12
0·180	26·81	14·31	32·50	71·43
0·254	28·61	17·22	31·00	65·18
0·468	32·01	22·08	33·00	57·61
0·722	40·63	21·13	29·50	46·54
0·871	45·25	21·96	19·50	30·82
0·947	45·41	23·15	18·50	27·10
1·306	46·96	28·29	11·50	16·45

From the preceding Table it will be seen that the breaking strains compared with those of the bars as received, have been considerably reduced throughout the entire series, although at no time did the temperature reach the A_1 point. As compared with the 620° C. (1,148° F.) bars annealed for half-an-hour, these soaked bars also show a diminution in the breaking strain, which, in the 0·871 per cent. carbon bar, reaches to about 18 per cent. The elastic limit is in every instance less in the soaked than in the annealed bars. The elongation and reduction of area are, however, as a rule, much greater than in the bars annealed for only half-an-hour. This increase is more marked in the high-carbon bars. It is also of interest to note that the bars containing 0·871, 0·947, and 1·306 per cent. carbon have each practically the same breaking stress. Photo-micrographs taken from this set of bars are given on Plate 24, and it will be seen that but little segregation of the iron carbide in the pearlite has taken place. It follows, therefore, that the general diminution of strength and the increased extensibility and reduction of area must be due to an increased plasticity of the ferrite.

In the low-carbon steels this change of properties has been ascribed to the formation of large ferrite grains, which has been noted by Stead* and others; but the size of the ferrite grains in the bars containing more than 0·18 per cent. of carbon has not been altered in the least degree by this treatment, so that the additional ductility must be due to an increased plasticity within the grains themselves as stated above.

Soaking bars at 720° *C.* (1,328° *F.*) *for Twelve Hours.*—The mechanical properties of these bars are given in Table 8, and are also plotted in Fig. 15, Plate 7:—

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* Journal, Iron and Steel Institute, 1903, II.

TABLE 8.

Bars soaked at 720° C. (1,328° F.) for Twelve Hours.

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	20·00	11·67	42·50	73·21
0·180	27·75	7·63	29·50	61·11
0·254	28·18	15·81	31·00	57·28
0·468	29·31	11·76	30·50	42·70
0·722	38·11	16·16	21·00	35·97
0·871	39·39	15·28	19·50	29·69
0·947	33·73	14·11	23·50	35·44
1·306	33·38	11·69	26·50	34·50

In a very complete investigation by Professor Heyn,* of Charlottenburg, on the heat treatment of mild steel, he found by means of bending tests that the fracture of overheated mild steel generally shows a close grain, although this is not necessarily always the case and depends on the rate of cooling. The structure of overheated steel usually shows large ferrite crystals, but he does not consider such structure a proof that overheating has taken place, as the same structure may be produced by prolonged heating between 700° C. (1,292° F.) and 890° C. (1,634° F.), although such structures are not necessarily accompanied by brittleness. It will be seen on reference to the above Table and the photo-micrographs shown on Plate 25 that, although the ferrite grains of the low-carbon steels are large, yet they are not brittle.

As would be theoretically expected, the photo-micrographs show that a considerable change has been brought about in the distribution of the Fe_3C in the bars by this treatment.

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* Journal, Iron and Steel Institute, 1902, II, page 73

Since this set of bars has been heated above A_1, and the cooling conditions were the same as for the bars annealed for half-an-hour at 720° C. (1,328° F.), any alteration in the mechanical properties of the high-carbon bars will be due to a change of the distribution of the carbide or to its decomposition, while, in addition, in the steels containing less than 0·722 per cent. carbon, another factor will be introduced, namely, the structure which the undissolved ferrite assumes during soaking, more especially as regards the greater cohesion of the cleavage planes of the grains. On comparing the breaking strains plotted in Fig. 15, Plate 7, with those of the bars annealed for half-an-hour at 720° C. (1,328° F.), Fig. 10, Plate 5, it will be seen that they are, for all practical purposes, the same in both the soaked and the annealed specimens as far as the 0·722 per cent. carbon bars. In the last three of the series of the soaked bars they are considerably less than in the corresponding annealed bars, and this is most marked in the 1·306 per cent. carbon steel where there is a decrease in strength of 17·2 tons per square inch. The reduction in the strength of these bars is interesting, as it shows that prolonged heating, at a temperature which is only a few degrees above the A_1 point, causes a marked difference in the structure of the steel. The rate of cooling through the Ar_1 point was, in this instance, slow, about twelve minutes being necessary to complete the change. This was, of course, due to the prolonged heating of the muffle, causing the surrounding brickwork to become so hot that cooling was retarded, and also to the initial temperature of cooling being so near the critical point. This slow cooling would also tend to increase the size of the grains of the structure.

Photo-micrographs of the 0·722, 0·871, and the 1·306 per cent. bars are given on Figs. 95, 96, and 97, Plate 25, at a magnification of 1,600 diameters, from which it will be seen that the structures are abnormal, there being no pearlite owing to the cementite having separated in the form of small rounded masses. The low-carbon steels of this series showed large ferrite grains and small carbide areas, when viewed under the low powers of the microscope. Photo-micrographs taken at 140 diameters of the 0·130, 0·180, and the 0·468 per cent. carbon bars are shown on Figs. 92, 93, and 94, Plate 25.

On comparing the mechanical results of this experiment with those of the bars soaked for twelve hours at 620° C. (1,148° F.), Plate 24, it will be found that the breaking strains of both sets of bars up to 0·721 per cent. of carbon are practically the same, which is exactly what one would expect from theoretical considerations. From this point the strengths of the bars soaked at 720° C. (1,328° F.) become considerably less than those soaked at the lower temperature, the maximum difference being reached at the 1·306 per cent. carbon bar, which is actually 13·6 tons per square inch weaker than that soaked at 620° C. (1,148° F.). The limits of elasticity are irregular in the series soaked at 720° C. (1,328° F.), and are considerably lower than in the corresponding bars treated at 620° C. (1,148° F.), except in the case of the 0·130 per cent. carbon steel.

The first six bars of the two series do not differ very widely in elongation and reduction of area, although those soaked at the lower temperature give rather higher results. This is not, however, the case with the last two bars of each set, the elongation and reduction of area of the bars soaked at the higher temperature being considerably in excess of those of the other series, the 0·947 bar showing 5 per cent., and the 1·306 bar 15 per cent. more elongation than the corresponding bars soaked at 620° C. (1,148° F.).

Soaking Bars at 900° *C.* (1,652° *F.*) *for Twelve Hours.*—This temperature was mainly chosen as it has been so frequently recommended by many workers, notably Stead,* as a suitable one for reheating low-carbon steels which have become brittle from various causes, such as prolonged annealing either immediately below or above the A_1 point, overheating, or mechanical work. The bars were treated in a gas-muffle in a similar manner to the others, but the rate of cooling through the Ar_1 point was considerably more rapid than in the case of the soaking at 720° C. (1,328° F.). This was, of course, mainly due to the higher initial temperature of cooling. The bars soaked at 900° C. (1,652° F.), with the exception of the 1·306 per cent. carbon steel, have their constituents completely dissolved, and, provided no decomposition of the carbide takes place, they should, theoretically, on cooling, possess satisfactory mechanical properties, since their structure is entirely re-formed by this treatment. The mechanical properties of these bars are plotted in Fig. 16, Plate 8, and are also given in Table 9:—

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* Journal, Iron and Steel Institute, 1903, II.

TABLE 9.

Bars soaked at 900° *C.* (1,652° *F.*) *for Twelve Hours.*

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture Per cent.
0·130	—	—	—	—
0·180	26·91	20·62	37·00	58·80
0·254	29·55	25·09	29·00	57·50
0·468	29·91	25·58	30·00	43·50
0·722	43·21	38·74	12·50	14·00
0·871	49·32	42·75	11·00	15·30
0·947	47·76	36·07	11·90	11·00
1·306	44·41	38·04	10·00	11·70

The low breaking strain of the soaked 1·306 per cent. carbon bar is evidently due to the structure being broken up into tiny particles of cementite, owing to this constituent not being entirely dissolved at this temperature and to fresh grains of it being formed during the subsequent cooling. The structure thus becomes fine grained and the strength is lowered. In this series, as in the annealings at 720° C. (1,328° F.), the maximum strength occurs in the 0·871 (saturated) steel.

When the above results are compared with those of the bars annealed at 620° C. (1,148° F.), Table 2 (page 26), and Fig. 9, Plate 4, it will be seen that the breaking strains of the soaked bars are all lower on an average by about 6 tons, the difference being least in the second bar of the series. The elongations are, however, much greater in the case of the soaked bars up to 0·468 per cent. of carbon and lower in the others. As regards reduction of area, the soaked bars are all lower, except that containing 0·254 per cent. of carbon.

It is interesting to note that the bars soaked at 900° C. (1,652° F.) give higher breaking strain and elastic limits for the whole series than those soaked at 720° C. (1,328° F.). The elongation is, however, greater only in the bar containing 0·180 per cent. of carbon. Beyond this point this condition is reversed, the bars soaked at 720° C. (1,328° F.) giving higher results for the rest of the series. The reduction of area is, with one exception, greater in the bars soaked at 720° C. (1,328° F.).

The breaking strains of the bars soaked at 900° C. (1,652° F.) agree well with those of the bars annealed for half-an-hour at the same temperature, practically the only discrepancy occurring in the 0·947 bars, the annealed bar being stronger than the soaked bar by 3·36 tons per square inch.

The elongation is, on the whole, greater in the soaked bars, but this does not also apply to the reduction of area; in this property the soaked and annealed bars agree fairly well in four cases, but in the 0·722 and the 0·947 steels the soaked bars are lower than the annealed ones. The annealed 1·306 bar, however, gives less elongation than the soaked one.

The limit of elasticity in these soaked bars is particularly high throughout the whole series, and it will be observed that in the 0·180, 0·254 and the 0·468 soaked bars it is roughly on an average 30 per cent. higher than in those annealed at the same temperature.

For practical purposes this fact is probably of the greatest importance, as it lends weight to the view that, with a suitable ordinary carbon steel, it may be possible to produce, by annealing alone, a metal which will be suitable for such purposes as the construction of gun-tubes and axles. As all manufacturers of ordnance know, it is difficult to obtain a uniform tensile strength and elastic limit in a large gun ingot by quenching in oil and subsequent annealing. The quenching is always a delicate operation on account of the size of the ingot under treatment, and it occasionally happens that the whole, or part of it, has fallen below the temperature of the Ac_1 point before the ingot is actually immersed in the oil, the result being an ingot with a low limit of elasticity. There is also a considerable amount of danger in re-heating a gun-tube during the process of tempering. A gun-tube which has been improperly quenched and annealed is a considerable source of danger, especially when, after the erosion of its bore by firing, a "liner" is introduced. If the original tube has not been properly quenched, but the "liner" has received correct treatment, a space will gradually develop, during use, between the "liner" and the tube, owing to the low elastic limit of the latter, and this will probably end in the fracture of both tubes. Guns with steel tubes, strengthened externally with wrought-iron coils, have been known in some instances to burst * explosively. Although this last statement presents an extreme case, since wrought-iron has a very low elastic limit, it nevertheless shows the importance of using material as homogeneous as possible in the construction of a piece of ordnance. By using annealed steels for such purposes, the possibility of obtaining a homogeneous gun would be much greater than by quenching in oil and annealing. Of course it would be necessary to use steel containing rather more than 0·35 per cent. of carbon for this purpose, in order to obtain the necessary limit of elasticity; but, even then, it is highly probable that such a steel would withstand the effects of shock better than an ordinary oil-tempered gun steel, on account of its more stable condition. The necessary mechanical properties for the construction of ordnance have been obtained in soaked and slowly cooled low-carbon "special" steels, and Table 9 (page 44) certainly indicates the possibility of the use of an ordinary "soaked" carbon steel for this purpose. If similar conditions as regards mechanical properties can

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* Morgan. Handbook of Artillery Matériel, page 3.

be obtained on a large scale from annealed ordinary carbon steels, there will be the additional advantage which such steels offer in their power of withstanding resistance to percussion. The elastic limits given in this Table are the more remarkable, as the steels contain such small percentages of manganese, averaging not more than 0·2 per cent. Further, it is well known that imperfect quenching sets up internal strains in steel which are not entirely eliminated by the subsequent annealing, owing to the variation in the density of the metal throughout the mass. That this variation is considerable is well shown in Table 9A compiled by Metcalfe and Langley:—

TABLE 9A.

Percentages of Carbon.	Specific Gravity.						
	Of the ingot.	Rolled, but unhardened.	Hardened at 700° C. (1,292° F.)	Hardened at about 800° C. (1,472° F.)	Hardened at about 900° C. (1,652° F.)	Hardened at about 1,100° C. (2,012° F.)	Hardened at about 1,250° C. (2,282° F.)
0·529	7·481	7·844	7·831	7·826	7·823	7·814	7·818
0·649	7·829	7·824	7·806	7·849	7·830	7·811	7·791
0·841	7·824	7·829	7·812	7·808	7·780	7·784	7·789
0·871	7·818	7·825	7·790	7·773	7·758	7·755	7·752
1·005	7·807	7·826	7·812	7·789	7·755	7·749	7·744
1·079	7·805	7·825	7·811	7·798	7·769	7·741	7·690

In a steel which has been heated for some considerable time above its critical points these strains no longer exist, and the advantage of using such a steel, provided it satisfies the condition of strength, &c., is obvious. An ordinary gun-steel which has been quenched in oil at about (871° C.) 1,600° F., and afterwards annealed at a temperature of about (482° C.) 900° F., is accepted if it satisfies the following conditions:—

1. The test-piece before testing is provided with two gauge-points accurately adjusted 2 inches apart, and is subjected in the testing machine, in the first instance, to a load of 21 tons per square inch; should the machine record any yielding point before this load has been reached, the same is noted. The load is next entirely removed and the test-piece measured. The permanent elongation under the load of 21 tons per square inch must not exceed 0·03 inch. The load is then again applied until the breaking point is reached, and, should the breaking strain be less than 34, or more than 44 tons per square inch, the thermal treatment of the steel is repeated. This is also done should the elongation be less than 17 per cent. On comparing the above tests with those obtained from the bars soaked at 900° C. (1,652° F.), Fig. 16, Plate 8, it will be seen that, by arranging the percentage of carbon correctly, it is possible to obtain a metal possessing suitable properties for the manufacture of ordnance, and there is every reason to believe that such a metal would have the additional advantage of an increased resistance to "shock," as has already been pointed out.

The necessity of obtaining a good tough steel with a high elastic limit also applies in the case of axles. The effects on the structures of axles when submitted to oil-quenching treatment will be described later under "oil-quenching."

Soaking bars at 1,200 *C.* (2,192 *F.*) *for Twelve Hours.*—This set was soaked at this high temperature mainly to determine the effects of the decomposition of the Fe_3C in the high-carbon steels on their mechanical properties.

The results of the mechanical tests are plotted in Fig. 17, Plate 8, and are also given in Table 10:—

TABLE 10.

Bars soaked at 1,200° *C.* (2,192° *F.*) *for Twelve Hours.*

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent
0·130	—	—	—	—
0·180	25·27	20·76	18·00	59·30
0·254	24·86	17·00	12·50	56·80
0·468	29·10	23·79	16·00	38·80
0·722	40·17	29·91	11·00	11·30
0·871	29·55	21·65	20·00	40·20
0·947	24·02	20·09	20·00	37·50
1·306	35·93	26·77	33·00	21·70

On comparing the above results with those of the bars soaked at 900° C. (1,652° F.), it will be found that, up to the 0·722 per cent. carbon steel, the breaking strain, although less in the present instance, does not differ widely. In the bars with a higher percentage of carbon, however, the breaking strain is much lower, the decrease in the last three bars being 19·8, 23·7 and 8·5 tons respectively. As would be expected, the elastic limit too is lower, while there is a well-marked increase in both the elongation and reduction of area, especially in the three high-carbon bars. This considerable alteration in their mechanical properties is due, to some extent, to the partial decomposition of the Fe_3C into amorphous carbon and iron, and also to the fact that the masses are now composed of large crystals, which are bordered more or less by straight lines. Photo-micrographs of such crystals are shown on Fig. 133, Plate 35, and on Fig. 143, Plate 36, at magnifications of 20 and 140 diameters respectively. The former was prepared from a gun ingot, which had not been reheated, while the latter was prepared from an ingot as cast, containing 0·18 per cent. of carbon.

It is well known that by heating high-carbon steels to 1,200° C. (2,192° F.) they become "burnt," when dark coloured crevices develop between the crystals, even although the steel has been allowed to cool slowly. Photo-micrographs of a die steel containing 0·8 per cent. of carbon, which has been "burnt" and then slowly cooled, are shown in Figs. 159 and 160, Plate 39, at magnifications of 140 and 850 diameters respectively. The dark crevices or patches, above referred to, are clearly visible in both figures.

In this series the maximum strength occurs in the 0·722 per cent. carbon bar, and the minimum reduction of area also occurs at the same point. The elastic limit, as compared with the breaking strain, is particularly high throughout the series.

It is interesting to note that the elongation is considerably less in the soaked than in the bars annealed at 1,100° C. (2,012° F.), while the reduction of area is practically the same in both cases. In the higher carbon bars, however, the elastic limit and reduction of area are greatly increased.

That the changes in the mechanical properties of the bars soaked at 1,200° C. (2,192° F.) are due to prolonged heating is proved by the fact that the bars annealed for half-an-hour at 1,100° C. (2,012° F.), which were cooled at approximately the same rate as the former, do not differ very greatly from bars annealed at much lower temperatures. The most noteworthy features in this set are the very great elongation and reduction of area in the three high-carbon bars.

HARDENING EXPERIMENTS.

Hardening bars.—By heating steels to the hardening temperatures, some or all of the iron carbide is dissolved in the iron, and the latter is restrained from reverting to its soft condition by sudden cooling. Within certain limits, the more rapidly the heat is abstracted from the bar the more effective will be the hardening. The rate at which the heat is abstracted from the steel and the final temperature of the quenching liquid greatly influences the hardness of the metal. It is upon this that the various properties of the numerous nostrums for hardening steel depend. The temperature of the bath must not be much altered during the quenching of the metal, or the hardening of the bar will not be uniform; therefore, in order to prevent a large rise of temperature during the quenching, it is necessary to employ a considerable volume of liquid. At one time it was generally believed that it was merely necessary to heat steel containing say 0·8 per cent. carbon to its A_1 point, or slightly above it, in order to obtain effective hardening in water, but it has been proved by the author (Sir W. Roberts-Austen), at the Royal Mint, that tools, such as steel dies, are not properly hardened in water at temperatures much below 850° C. (1,562° F.), and care must be taken that the whole mass of steel is at this temperature at the time of quenching. Steels containing more or less carbon will, of course, require higher temperatures than those near the saturation point. The theoretical points are indicated by lines in the equilibrium curve, Fig. 7, Plate 3.

Steels are either "quenched right out" in a liquid, or they are quenched according to the broken hardening method of Jarolimek, which consists in cooling the steel quickly to 400° C. (752° F.) and then allowing it to cool slowly. Such a quenching is generally done by dipping the steel into fused lead or tin, the temperature of which is below that point.

For the purposes of this Report, however, only the first method was employed, and the tempering effect of Jarolimek's method was obtained in the oil-quenched bars by subsequent annealing at definite temperatures.

On account of the delicacy of the operation of quenching, it is necessary to use the utmost caution to ensure the correct temperature of the steel at immersion, and also the instantaneous placing of the metal in the bath on removal from the furnace. It is of paramount importance that this latter operation be expeditiously carried out, as any delay may lead to quenching at too low a temperature, and the results thus obtained be rendered inaccurate.

The liquids generally used in practice for quenching steels vary considerably. The most common hardening liquid is water, although that cannot be considered altogether satisfactory, as the steam developed on the surface of the metal prevents proper conduction, resulting in an imperfect quenching. The conductivity of water is occasionally improved by the addition of a small percentage of such substances as sulphuric acid, salt and sal ammoniac ; it may be diminished by the addition of such substances as milk of lime, soap or methylated spirit. Mercury is sometimes employed, it having the advantage of cooling the steels very quickly, and, if in sufficient bulk, hardening uniformly, owing to the fact that it does not give off sufficient vapour to prevent intimate contact. A good method of quenching small objects is to immerse them in a liquid, such as water which is floating on a bath of mercury. Some very fine specimens of martensite have been obtained in the Research Laboratory at the Royal Mint by employing this method. Oils are used to a great extent for steel which is required to withstand rapid alternations of strain within its elastic limits. For this purpose fish oils, on account of their cheapness, are largely employed. Tallow and mixtures of oil and tallow are also frequently used. Mercury, oil and fats are in most cases cooled by water-tanks. For the purposes of this Research, it was considered inexpedient to add either acids or salts to the water used for quenching the steels, but in every case the bars were vigorously stirred in the water so as to ensure good contact. Several series of bars were quenched in water and others were quenched in oil ; with one exception, however, all the bars quenched in oil were afterwards reheated to some definite temperature.

It will be well to describe, at this point, the manner in which the operation of quenching was effected :—A piece of wrought-iron tube was placed in a gas-muffle, and the test-piece, with a thermo-couple attached, was inserted. The gas was regulated until the required temperature was obtained, and the bar was kept at this temperature for five minutes. It was then suddenly removed from the tube, by means of the couple-wire, and instantly immersed in the bath, which was maintained at 20° C. (68° F.). It remained there until it attained the same temperature as the liquid in the bath, during which time it was kept in a state of vigorous motion.

The results obtained by "water-quenching" at definite temperatures will now be considered.

Quenching bars at 720° *C.* (1,328° *F.*) *in Water.*—By quenching bars at this temperature in water, the whole of the original pearlite will be retained in the form of sorbite or martensite. The pearlite in steels below the saturation point will dissolve, but little ferrite and only a small amount of Fe_3C will be taken up by those above it. The results of the mechanical tests of this set of bars are shown in Table 11, and are also plotted in Fig. 18, Plate 9 :—

TABLE 11.

Bars quenched at 720° *C.* (1,328° *F.*) *in Water at* 20° *C.* (68° *F.*).

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	36·18	*	22·00	60·20
0·180	44·82	*	14·00	46·92
0·254	43·20	*	13·70	45·96
0·468	39·60	*	21·00	48·78
0·722	51·00	*	17·50	32·92
0·871	54·84	*	15·80	29·58
0·947	56·04	*	12·00	24·78
1·306	56·94	*	8·80	15·84

* No definite yield point.

It will be seen that the mechanical properties of the bars after this treatment, when compared with those of the original bars, Table 1 (page 24), and Fig. 8, Plate 4, nearly confirm the statements contained in the excellent Paper of Brinell and Wahlberg,* to the effect that: "the changes in the steel, in consequence of hardening at 750° C. (1,382° F.) without subsequent annealing, might be compared with those effected by cold working; the action of which treatment towards reducing the ductile properties is also more effective in softer materials than in harder ones." Our results, as regards breaking strain and elongation, except in the case of the three low-carbon steels, are in accordance with the views expressed by Brinell and Wahlberg. It is evident, however, that hardening at 720° C. (1,328° F.) does not cause a notable increase in the breaking strains of steels as compared with those "as rolled," except in the case of low-carbon bars, such as the first three of this series. Curiously enough the reduction of area of the quenched bars is very considerably in excess of that of the untreated bars. On comparing the results in Table 11 (page 53) with those of the "normalised" bars in Table 2 (annealed at 620° C.), it is evident that, as regards breaking strain, elongation and reduction of area, the differences are practically confined to the 0·180, 0·254 per cent. carbon bars. In this respect our results are also in agreement with those of Brinell and Wahlberg. Sections from these bars, when examined microscopically, show that the pearlite areas have been converted into martensite or sorbite by the quenching, the hardening being thus effected. The structures obtained by quenching a steel containing 0·47 per cent. of carbon at 720° C. (1,328° F.) are shown in Figs. 139 and 140, Plate 36, at magnifications of 140 and 850 diameters respectively. It will be seen that the steel is composed of ferrite and martensite or sorbite.

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* Journal, Iron and Steel Inst. 1901, II, page 247.

Quenching bars at 800° C. (1,472° F.) in Water.—The structural effect of quenching the bars at 800° C. (1,472° F.) is the solution of more ferrite or cementite than in the case of the quenching at 720° C. (1,328° F.), and consequently the spaces occupied by the martensite or sorbite are greater. The effect of this change of structure is to harden the bars and increase their tenacity.

The results of the mechanical tests are plotted in Fig. 19, Plate 9, and given in Table 12:—

TABLE 12.

Bars quenched at 800° C. (1,472° F.) in Water at 20° C. (68° F.)

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	38·88	†	21·70	59·94
0·180	49·02	†	14·50	51·60
0·254	52·38	†	6·50	8·94
0·468	61·26	†	1·60	6·00
0·722	*	—	—	—
0·871	*	—	—	—
0·947	*	—	—	—
1·306	70·02	†	0·50	1·32

* Broke in clips. † No definite yield point.

Unfortunately, as shown above, the 0·722, 0·871 and the 0·947 per cent. carbon bars broke in the clips; the others are, in their mechanical properties, allowing for the difference of temperature, entirely in agreement with Brinell's second series of quenchings at 850° C. (1,562° F.). On comparing the breaking strains of this series with those of the rolled bars, it is evident that the quenching has very considerably increased the tenacity of the first four bars, and the strength of the 1·306 per cent. carbon bar has also increased from 56·11 tons to 70·02 tons per square inch.

On comparing the results in this Table with those of the "normalised" bars (620° C. annealings, page 26), it will be found that the breaking strains of the quenched bars are considerably increased, while as regards elongation and reduction of area there is a very marked diminution.

Photo-micrographs taken from this set of bars exhibit larger carbide areas than those of the quenchings at 720° C. (1,328° F.); the bars containing less than 0·89 per cent. (the eutectoid) of carbon being made up of ferrite and martensite and presenting structures, under a magnification of 1,600 diameters, similar to that shown on Fig. 141, Plate 36. The bars containing more than the eutectoid are, of course, made up of martensite and cementite.

Quenching bars at 900° *C.* (1,652° *F.*) *in Water.*—The effect of quenching at this temperature is to convert the structures of the bars from the 0·254 to the 0·871 per cent. carbon steel, inclusive, entirely into martensite. The 0·130, 0·180, 0·947 and the 1·306 per cent. carbon bars are, however, only partly converted into martensite, being mainly composed of cementite globules of various dimensions in a matrix of ferrite and martensite.

A photo-micrograph of the 0·722 per cent. carbon bar is shown on Fig. 98, Plate 26. This is typical of the martensite produced by quenching at this temperature. Figs. 99 and 100, on the same Plate, represent, respectively, the 0·947 and the 1·306 per cent. carbon bars, from which it will be seen that both steels are, as stated above, composed of cementite embedded in matrices of ferrite and martensite.

The results of the mechanical tests are plotted in Fig. 20, Plate 10, and are given in Table 13 (page 57).

There are, unfortunately, no results in Brinell's Paper for comparison with these quenchings, as Brinell did not treat any bars at this temperature. On comparing the mechanical properties of the bars dealt with in this Table with those of the original bars, it will be found that there is a noticeable increase in the breaking strain and a remarkable decrease in the elongation of the quenched bars containing from 0·180 to 0·722 per cent. of carbon.

TABLE 13.

Bars quenched at 900° C. (1,652° *F.*) *in Water at 20° C.* (68° *F.*).

Carbon. Per cent.	Breaking Strain Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture Per cent.
0·130	32·34	24·30	28·20	76·26
0·180	49·92	†	6·50	35·28
0·254	70·32	†	3·80	13·44
0·468	55·44	†	1·00	2·64
0·722	61·98	†	1·00	2·53
0·871	26·04	†	2·00	2·16
0·947	21·60	†	Nil	Nil
*1·306	—	—	—	—

* Broke in clips. † No definite yield point.

The bars with 0·468, 0·722, 0·871, and 0·947 per cent. of carbon are all absolutely brittle, and in no case does the elongation or reduction of area exceed 2·64 per cent.

When the mechanical properties of these bars are compared with those of the "normalised" ones (620° C. annealings, page 26), a noteworthy point is the great increase in breaking strain in the bars containing up to 0·722 per cent. of carbon. It will, however, be seen that the saturated and super-saturated steels are remarkably weak.

On examining these steels microscopically, it is interesting to note that in all those in which the martensite is well defined the breaking stress is high, but in those in which the globular cementite appears, *i.e.* in the 0·871, 0·947, and the 1·306 per cent. carbon bars, the strength is very low. The former structure is well illustrated in Fig. 98, Plate 26, and the latter in Figs. 99 and 100, in the same Plate. The more homogeneous structure of the lower carbon bars is also conducive to greater strength.

Quenching bars at 1,200° *C.* (2,192° *F.*) *in Water.*—This series is an interesting one, as the ductility has been entirely destroyed in the bars containing from 0·468 to 1·306 per cent. of carbon inclusive, and almost entirely destroyed in the 0·180 and 0·254 bars.

The mechanical properties of the bars are plotted in Fig. 21, Plate 11, and are also given in Table 14 :—

TABLE 14.

Bars quenched at 1,200° *C.* (2,192° *F.*) *in Water at* 20° *C.* (68° *F.*).

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	45·29	*	9·00	35·12
0·180	72·78	*	3·50	5·16
0·254	77·04	*	3·00	4·74
0·468	31·74	*	Nil.	Nil.
0·722	13·44	*	Nil.	Nil.
0·871	5·40	*	Nil.	Nil.
0·947	4·20	*	Nil.	Nil.
1·306	3·52	*	Nil.	Nil.

* No definite yield point.

It will be seen from this Table that the breaking strains of the first three bars are considerably greater than those of the corresponding bars quenched at 900° C. (1,652° F.), while the 0·468 and 0·722 per cent. carbon bars show a decrease of as much as 23·7 and 48·5 tons per square inch respectively. The three high-carbon bars exhibit all the properties of badly "burnt" steel, and have an average breaking strain of only about 4 tons per square inch. Beyond the 0·254 per cent. carbon bar, none of the steels show the least elongation or contraction of area.

When examined under the microscope, the sections taken from this series presented some interesting structures under magnifications of 140 and 1,600 diameters. The 0·130 and 0·180 per cent. carbon bars consisted of a mixture of well-defined martensite and ferrite, while the 0·254 bar was composed of large martensite crystallites, but there was an absence in the structure of the dark joints which are generally associated with burnt steel. Although the strength of the 0·468 bar was considerably less than when quenched at 900° C. (1,652° F.), yet there were still no dark joints visible. This was not, however, the case with the steel containing 0·722 per cent. carbon, the joints being faintly visible in this instance. Photo-micrographs of this steel are reproduced on Figs. 101 and 105, Plate 27, under a magnification of 140 and 1,500 diameters respectively, and the dark lines or joints, above referred to, can just be seen under the low magnification in Figs. 102, 103, and 104. In Fig. 105, under the high magnification, it is evident that the mass of the structure is composed of well-defined martensite.

In the photo-micrograph of low magnification of the 0·871 per cent. carbon bar, Fig. 102, the dark spaces between the grains are shown more plainly than in the last instance. The high magnification, Fig. 106, shows a larger variety of Martensite than in the 0·722 per cent. carbon bar. The low power photo-micrograph of 0·947 per cent. carbon steel, Fig. 103, presents a case in which the dark lines are both wide and numerous. Under the high power, Fig. 107, the grains are seen to consist entirely of martensite, as in the last example.

The dark lines are also present and well defined in the low power photo-micrograph of the 1·306 per cent. carbon bar, Fig. 104. The high power photograph, Fig. 108, proves that the grains themselves are composed of martensite, and shows the junction of three of the grains with the dark lines between them.

On comparing the results of the mechanical tests with the photo-micrographs, it is evident that the breaking strain decreases as the dark lines between the grains increase, and, where these lines do not exist, the steel is extremely strong; it therefore appears probable that these lines are the cause of the weakness in the last five bars of the series.

These dark lines have been stated to be due to oxide of iron enveloping the grains, but it is difficult to account for the presence of the oxide in the steel. It has already been pointed out in this Report that cementite, when heated to about 1,100° C. (2,012° F.), may be decomposed into iron and carbon, and, undoubtedly, in the high-carbon steels especially, the cementite around the original ferrite grains is actually partly decomposed before it is dissolved, thus depositing layers of carbon around the grains. When the mass is quenched at this high temperature the grains expand about 2 per cent. of their volume, and a general loosening takes place between them, thus producing the joints which give rise to the characteristic crumbliness of a burnt steel. The lines between the grains are not entirely spaces, although occasionally they are partly so; but they either contain, or are coloured by, a dark substance, which is most probably carbon. The fact that steel when burnt may have its physical properties restored by quenching three times at 900° C. (1,652° F.) in either boiling water, or in a mixture of colophony and boiled oil, should dispel any idea that the dark lines are due to iron oxide.* Forging at a low temperature for some time will also produce the same effect, the combined pressure and heat causing the carbon to re-form Fe_3C. Further, if the dark lines were merely spaces between the crystals, this fact would be at once evident under the microscope, when using a vertical illumination. In Fig. 130, Plate 34, is shown a photo-micrograph, at a magnification of 850 diameters, of a die steel containing 0·8 per cent. carbon which has been "burnt" and then quenched in water. The dark lines are quite visible.

The Oil-Hardening of Steel Bars.—When steel is quenched in oil at 80° C. (176° F.), the effect is to increase the tensile strength, but to a somewhat less extent than by quenching in water at 20° C. (68° F.); and also at the same time to increase the elastic limit and rather diminish the ductility. The result of oil-quenching at temperatures above 700° C. (1,292° F.) is the conversion, more or less completely, according to the temperature of quenching, of the original pearlite areas into sorbite or martensite. In low-carbon steels, however, the carbide areas increase in size, according to the temperature to which they are raised and the duration of the heating to which they are subjected before being plunged into the oil. On subsequent re-heating, the sorbite or martensite is converted into either granular or lamellar pearlite, according to the temperature to which it is subjected. From the following experiments it will be observed that the most suitable temperature for quenching steel, in order to obtain the best combined results as regards breaking strain, elastic limit and elongation, is about 900° C. (1,652° F.), and the most suitable temperature for re-heating, when elongation, and consequently resistance to shock, is not of paramount importance, is about 350° C. (662° F.). If however, the steel be required to withstand violent percussive action, as in a gun tube, then re-heating at a higher temperature, say, 600° C. (1,112° F.), will be found to be necessary, as such steel, when thermally treated in this way, although possessing a relatively high breaking strain and elastic limit, nevertheless has also a high percentage of elongation. This is demonstrated in the following experiments.

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* Professor Stansfield has shown recently, in a Paper to the Iron and Steel Institute (1903, II, page 433), that oxidation takes place in the flaws in bad cases of "burning," but he states that in such cases the metal can only be restored with great difficulty, if at all.

The bars now being dealt with were quenched in the manner already described under "Water Quenching," but, in this case, a larger volume of oil than of water was used. The average temperature of the oil bath during quenching was about 80° C. (176° F.). The bars were kept in vigorous motion until they were of the same temperature as the bath. When all the bars of a series had been treated in this way, they were wired together and packed in the large iron tube, which has already been described. This was then placed in a muffle, as in the experiments on "Annealing," and two thermo-couples were inserted (in the manner previously mentioned, page 17) to indicate the temperature of the re-heating. In order to imitate the cooling conditions of large masses of metal, the bars, after reaching the required temperature, were allowed to cool in the closed muffle, and, when cold, were taken out, cleansed from lime, and mechanically tested. The bars quenched at 870° C. (1,598° F.) and reheated to 350° C. (662° F.) yielding such excellent mechanical results, it was thought advisable to quench two other sets of bars at approximately the same temperature, and to reheat them to 600° C. (1,112° F.) instead of to 350° C. (662° F.). Two sets of bars were accordingly quenched at 800° C. (1,472° F.) and 900° C. (1,652° F.) respectively, and afterwards reheated to 600° C. (1,112° F.), to ascertain definitely to what extent the results obtained at these temperatures would be beneficial for practical purposes.

Oil-Quenching in Practice.—The usual practice adopted in the oil-quenching of guns, axles, and similar masses of steel, is to heat them to a temperature varying from 800° C. (1,472° F.)—which is the most usual—to 850° C. (1,562° F.); then to quench in oil at about 80° C. (176° F.); and afterwards to reheat from about 550° C. (1,022° F.) to 650° C. (1,202° F.). Some manufacturers never heat above 350° C. (662° F.), whilst others go as high as 650° C. (1,202° F.), but a very common temperature is 550° C. (1,022° F.). The oil-quenching is performed in a large tank or well, which is usually sunk in the ground, into which the steel is immediately lowered on its withdrawal from the furnace. The steel is allowed to remain in the oil until practically cold, and is then taken out and reheated. The oil tank is sometimes surrounded with a water-jacket for the purpose of cooling it as rapidly as possible.

A number of photo-micrographs are given on Plates 34, 35, and 37, to illustrate the effects of oil-quenching, as produced in practice, in the manufacture of ordnance and large axles.

Quenching bars at 720° *C.* (1,328° *F.*) *in Oil at* 80° *C.* (176° *F.*).—This series of bars was quenched without subsequent annealing, in order to determine the actual difference of the properties of bars so quenched and those quenched at the same temperature and then annealed at 350° C. (662° F.).

Table 15 gives the results of the mechanical tests of this series of bars :—

TABLE 15.

Bars quenched at 720° C. (1,328° F.) in Oil at 80° C. (176° F.).

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches Per cent.	Reduction of area at fracture Per cent.
0·130	32·68	18·67	26·00	59·62
0·180	36·79	24·24	25·00	60·24
0·254	37·84	24·94	23·00	57·77
0·468	39·75	29·14	24·50	48·82
0·722	50·43	30·74	16·50	36·54
0·871	76·77	50·24	13·00	36·34
0·947	52·30	40·00	13·00	19·81
1·306	53·82	37·75	7·00	8·67

On comparing the above results (which are also plotted in Fig. 22, Plate 12) with those of the original bars, it will be found that they do not entirely agree with those of Brinell. Brinell states that the ultimate strain is increased by oil-quenching at 750° C. (1,382° F.) in bars containing 0·09, 0·16 and the 1·17 per cent. carbon, but is unchanged in bars with 0·25, 0·34, 0·44, 0·65, 0·79 and 0·947 per cent. of carbon. On the other hand, the bars experimented upon in this Report, with the exception of the 0·947 and the 1·306 per cent. carbon steel, are all stronger than the corresponding bars "as received,' *i.e.* before treatment. The increase of strength and elastic limit is most marked in the 0·871 per cent. carbon bar, which is practically a saturated steel, the strength having increased from 58·52 to 76·77 tons per square inch, and the elastic limit from 20 to 50·24 tons per square inch. This great increase of strength and elastic limit of the 0·871 bar is probably the most remarkable feature in this series. In elongation and reduction of area there is also a great increase, except in the 1·306 per cent. carbon bar.

On comparing the results for the breaking strain, elastic limit, elongation and reduction of area with those of the "normalised" bars (620° C. annealings), it will be observed that, excepting the saturated bar, these properties are in close agreement. In every case, however, in the oil-quenched saturated bars these properties greatly exceed those of the corresponding "normalised" bar.

Under the microscope the sections from this series exhibit either ferrite and sorbite or sorbite and cementite, according to the carbon content of the bars. It will be remembered that the bar containing 0·871 per cent. carbon was the strongest of the series under several forms of heat treatment, and, in all instances, this was due to its homogeneous structure. In the present case the whole mass has been transformed from pearlite into a mass of sorbite and to this change of structure its very great strength, as compared with the other bars of the set, is due. In steel containing less than 0·8 per cent. carbon the strength and elastic limit, as compared with those of the saturated steel, are lowered by the ferrite crystals interspersed throughout the metal. Similarly, in steel containing more than 0·9 per cent. carbon, the interspersed cementite is the cause of the loss of strength. At a higher temperature of quenching when the cementite has had an opportunity of passing into solution, it is probable that the higher carbon bars will be stronger than the saturated bar.

Quenching bars at 720° *C.* (1,328° *F.*) *in Oil at* 80° *C.* (176° *F.*) *and reheating to* 350° *C.* (662° *F.*).—From Table 16 (page 65), and from Fig. 23, Plate 13, it will be observed that a great change has been brought about in the mechanical properties of the bars by tempering at 350° C. (662° F.).

Comparing the above results with those of Table 15 (page 63) which gives the properties of the bars simply quenched at 720° (1,328° F.) in oil, it will be found that the following are the effects of the tempering:—The ultimate strengths of the bars have, on the whole, been diminished; the elastic limits have not been lowered in nearly so great a proportion (except in the saturated steel); and the elongations have in most cases been increased.

TABLE 16.

Bars quenched at 720° C. (1,328° F.) in Oil at 80° C. (176° F.), and subsequently reheated to 350° C. (662° F.).

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	22·13	11·89	41·00	75·94
0·180	31·10	16·83	29·00	59·88
0·254	34·15	22·56	25·00	57·87
0·468	41·83	25·43	20·00	50·12
0·722	48·70	27·47	21·50	36·00
0·871	53·94	27·38	13·50	27·63
0·947	54·63	33·52	12·00	18·64
*1·306	57·75	40·13	6·50	—

* Broke outside gauge points.

Brinell found that bars hardened in oil at 750° C. (1,382° F.) and reheated to 350° C. (662° F.) lost the increased ultimate strain produced by the hardening, and did not differ appreciably from the normal steel. It will be seen that the results of the present experiments fully confirm his views in a very remarkable way. Brinell's conclusions, however, with reference to the elastic limits being sometimes raised by tempering at 350° C. (662° F.), are only borne out in one instance, viz. the 1·306 per cent. carbon bar. His views with regard to the increase in ductility by reheating are also practically confirmed.

When examined microscopically under a high power, this series of bars showed very different structures from those of the oil-quenching at 720° C. (1,328° F.) without subsequent tempering. The whole of the carbide areas were found to consist of minute pearlite, similar to that shown in Fig. 138, Plate 35, instead of sorbite. It is, therefore, evident that the effect of the reheating at 350° C.

(662° F.) was to break up the sorbite or martensite into very minute pearlite, and it is due to the presence of this pearlite that the low-carbon steels have an increased elongation and offer greater resistance to the effects of "shock."

The spaces occupied by the carbide areas in this and the last series are, on account of the low temperature at which the quenching was performed, scarcely larger than in the original bars.

Quenching bars at 870° *C.* (1,598° *F.*) *in Oil at* 80° *C.* (176° *F.*) *and reheating to* 350° *C.* (662° *F.*).—This quenching temperature of 870° C. (1,598° F.) was chosen in preference to 900° C. (1,652° F.), as it is a favourite temperature for the quenching of ingots destined for the manufacture of ordnance and axles, while the subsequent annealing to 350° C. (662° F.) is adopted by many manufacturers.

Table 17 gives the mechanical results obtained from this set of bars :—

TABLE 17.

Bars quenched at 870° *C.* (1,598° *F.*) *in Oil at* 80° *C.* (176° *F.*), *and subsequently reheated to* 350° *C.* (662° *F.*).

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	21·50	15·69	39·50	76·44
0·180	36·12	23·81	23·50	65·38
0·254	41·13	28·81	24·50	62·14
0·468	54·65	42·52	25·00	47·17
0·722	78·59	36·54	23·50	38·08
0·871	90·68	67·55	10·50	31·82
0·947	102·52	66·73	7·00	16·99
1·306	90·57	56·29	5·50	10·57

The above results are also plotted in Fig. 24, Plate 14, and an examination of the curves will show that the mechanical properties obtained are probably the most remarkable in the whole series of experiments.

On comparing the above breaking strains with those of the last series of bars, it will be found that they are considerably higher in the present case, the maximum strength occurring in the 0·947 bar, which has a breaking stress of no less than 18 tons greater than the bar quenched at 720° C. (1,328° F.) and reheated to 350° C. (662° F.). It will also be noted that the maximum breaking strain, in this instance, does not occur in the 0·871 per cent. carbon bar, but in the 0·947 carbon bar just mentioned. The high ultimate strength of this bar is, doubtless, due to the complete solid solution of the cementite in the mass, and by the subsequent cooling in oil the entire structure is converted into sorbite, which is considerably more elastic and, at the same time, less brittle than martensite. It is possible that the low breaking stresses sometimes obtained by quenching high-carbon steel bars at about 900° C. (1,652° F.) in water are due to cracks produced in the metal by the sudden abstraction of heat. In the case of the oil quenchings, however, the oil being a poor conductor of heat the cooling is less rapid, and a more elastic mass (sorbite) with less tendency to brittleness is the result. Under these circumstances no fissures are developed, and a greatly increased strength is obtained.

Further, the tendency of sorbite to crack from internal strains is also less than that of martensite, the latter being considerably less dense than the former; consequently, the variations in density of different parts of the sorbite mass will be less than those of the martensite, and the probability of cracking in the latter will be greater.

It will be further observed that the elastic limit is, in every case, considerably higher than in the bars quenched at 720° C. (1,328° F.) in oil and reheated to 350° C. (662° F.), but, unlike the breaking strain, it reaches its maximum in the 0·871 and not in the 0·947 per cent. carbon bar.

In elongation and reduction of area the differences between the two series of bars are not great. The bars quenched at 870° C. (1,598° F.) and reheated to 350° C. (662° F.) give rather lower results in elongation in the 0·13, 0·18, 0·254, 0·871, 0·947 and the 1·306 bars than do those treated at the lower temperature; while in the 0·468 and the 0·722 bars the results are slightly higher. As regards the reductions of area, the differences are not sufficiently great to require special comment.

Photo-micrographs obtained from this series of bars are represented on Plate 28. From these it will be seen that, in the steels containing more than 0·18 per cent. of carbon, the greater portion of the ground mass is taken up by carbide areas. These carbide areas are made up of a minute form of granular pearlite, which is particularly well shown in the cases of the 0·722 and the 0·871 per cent. carbon bars, Figs. 113 and 114. The increased strength and elastic limit of these bars are undoubtedly due, in the bars containing low carbon, to the greater size of the carbide areas and also to the partial separation of the pearlite from the solid solution.

In Plates 35 and 37 several photo-micrographs are shown of steels which have been treated at these temperatures during the actual manufacture of guns and axles. On comparing those having a magnification of 1,600 diameters with the photo-micrographs on Plate 28, it will be observed that the structures are, for all practical purposes, the same.

Quenching bars at 1,000° *C.* (1,832° *F.*) *in Oil at* 80° *C.* (176° *F.*) *and reheating to* 350° *C.* (662° *F.*).—This series of bars is particularly interesting, as it shows that, for most purposes, the greatest combined elastic limit, tensile strength and elongation is probably obtained when steel bars are quenched below this point, as, for example, at about 870° C. (1,598° F.), and subsequently reheated to some temperature below Ar_1.

The mechanical results obtained from this set of bars are plotted on Fig. 25, Plate 15, and are also given in Table 18 (page 69).

On comparing the mechanical properties of these bars with those of the last, it will be observed that, with the exception of the 0·130 per cent. carbon bar, the breaking strains are less, the difference being most marked in the 0·871 and the 0·947 carbon steel.

The elastic limits are somewhat variable, being greater in the 0·130, 0·722, 0·947 and 1·306 bars, and less in the 0·180, 0·254, 0·468 and 0·871 bars.

TABLE 18.

Bars quenched at 1,000° *C.* (1,832° *F.*) *in Oil at* 80° *C.* (176° *F.*), *and subsequently reheated to* 350° *C.* (662° *F.*).

Carbon Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches Per cent.	Reduction of area at fracture. Per cent.
0·130	25·91	19·62	32·50	67·48
0·180	35·96	23·42	26·50	63·04
0·254	40·32	25·29	19·00	60·51
0·468	54·10	37·24	14·00	63·59
0·722	76·41	50·96	14·00	32·69
0·871	83·84	58·30	9·50	24·15
0·947	94·19	68·13	5·50	14·84
1·306	90·00	59·81	5·00	7·09

The elongations, with the exception of the 0·18 per cent. carbon bar, are, in most cases, much lower in the set of bars now being dealt with.

The reductions of area are, however, more varied; in the 0·130, 0·180, 0·254, 0·722, and the 0·871 per cent. carbon bars in the present series they are lower, and in the remaining bars higher, but the differences are not, in any case, very great.

From this experiment it is evident that a temperature of 1,000° C. (1,832° F.) is too high for quenching steel bars in oil, if it be desired to obtain the highest combined breaking strain, elastic limit and elongation. The difficulties of judging, by the eye, temperatures within 100° C. (212° F.) of above 900° C. (1,652° F.) are well known to steel workers, but the foregoing results plainly show the importance of quenching a steel within a narrow range of definite temperatures, although it may be necessary to employ some rough form of pyrometer for this purpose.

In this set, like as in the preceding one, the maximum breaking strain occurs in the case of the 0·947 bar, and is evidently due to the same cause.

Quenching bars at 800° *C.* (1,472° *F.*) *in Oil at* 80° *C.* (176° *F.*) *and reheating to* 600° *C.* (1,112° *F.*).—The mechanical properties of the bars which have received the above treatment are given in Table 19, and are also plotted in Fig. 26, Plate 16:—

TABLE 19.

Bars quenched at 800° *C.* (1,472° *F.*) *in Oil at* 80° *C.* (176° *F.*), *and subsequently reheated to* 600° *C.* (1,112° *F.*).

Carbon Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation of 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	21·42	19·78	38·00	70·60
0·180	36·16	29·82	26·00	57·00
0·254	—	—	—	—
0·468	41·06	31·92	17·00	52·30
0·722	58·47	49·90	17·50	38·90
0 871	53·11	46·86	15·00	32·60
0·947	45·97	35·70	12·00	12·90
1·306	46·86	42·50	7·50	22·00

By comparing the results given in this Table with those obtained after quenching the bars at 870° C. (1,598° F.) and reheating to 350° C. (662° F.), it will be observed that the breaking strains, although practically the same in both cases in the 0·130 and 0·180 per cent. carbon bars, are nevertheless very much lower in the steels of this series, which contain higher percentages of carbon. It will also be noted that the breaking strains of the 0·722, 0·871, 0·947, and the 1·306 bars do not widely differ from one another, as do those in the latter series. Although the breaking strains are considerably lower in the bars of this experiment, yet the elastic limits, as compared with the breaking strains, are relatively higher than in preceding series. In the elastic limits, as in the breaking strains, the 0·722, 0·871, 0·947, and the 1·306 bars are in tolerably close agreement. This rough uniformity of elastic limit and tensile strength is, doubtless, owing to the formation of that minute variety of pearlite which is shown in Fig. 136, Plate 35. In the 0·947 bar, which has been treated at 870° C. (1,598° F.), for example, the original martensite and sorbite have only been slightly changed by the reheating to 350° C. (662° F.), and the bar is therefore strong, having a breaking strain of 102·5 tons per square inch. If, however, this bar had been reheated to about 600° C. (1,112° F.), as the corresponding bar was in the present experiment, its breaking strain would have been considerably less. It is evident, therefore, that this approximate uniformity has been brought about by the development of this variety of pearlite at the higher reheating temperature. Further, as the strength of a steel is always dependent on its weakest constituent, and, as in the case of the four high-carbon steels enumerated above, the masses of the metal are mainly composed of an exactly similar minute pearlite which forms the weakest constituent, it is not surprising to find that the strengths and elastic limits are in close agreement with one another.

The elongation and reduction of area in this series of bars is hardly so great as would be expected from the results of the three previous quenchings in oil. Nevertheless the micro-structures of the steels quenched at 800° C. (1,472° F.) in oil and reheated to 600° C. (1,112° F.) indicate greater power of resistance to shock or percussive action than those tempered at 350° C. (662° F.) only, and it is therefore safe to conclude that the present series would, in this respect, be superior to those treated at 870° C. (1,598° F.) and subsequently tempered at 350° C. (662° F.). It will be observed that the maximum both of elastic limit and tensile strength occurs in the 0·722 per cent. carbon bar.

Quenching bars at 900° *C.* (1,652° *F.*) *in Oil at* 80° *C.* (176° *F.*) *and reheating to* 600° *C.* (1,112° F.).—The mechanical properties of the bars after treatment are as follows :—

TABLE 20.

Bars quenched at 900° C. (1,652° F.) in Oil at 80° C. (176° F.), and subsequently reheated to 600° C. (1,112° F.)

Carbon. Per cent.	Breaking Strain. Tons per square inch.	Elastic Limit. Tons per square inch.	Elongation on 2 inches. Per cent.	Reduction of area at fracture. Per cent.
0·130	24·55	15·62	40·70	72·0
0·180	30·13	24·55	30·00	58·5
0·254	31·24	25·89	26·20	58·4
0·468	35·71	29·02	27·20	51·0
0·722	50·44	44·63	17·50	33·3
0·871	52·68	46·85	15·50	30·0
0·947	49·10	40·18	17·00	28·0
1·306	51·32	42·40	13·00	21·0

These results are also plotted in Fig. 27, Plate 16.

On comparison with those of the last series of bars it will be found that the results do not differ greatly. The increased hardening effect, which one would expect to be produced by quenching at a higher temperature, is not apparent. The limits of elasticity are in fact actually lower, on the whole, in the bars quenched at 900° C. (1,652° F.). The elongations and the reductions of area, on the other hand, are greater. It appears, therefore, that by quenching steel bars at 900° C. (1,652° F.) in oil and reheating to 600° C. (1,112° F.) a more ductile metal is obtained than by quenching at 800° C. (1,472° F.) under the same conditions.

The maximum elastic limit and tensile strength occurs in the 0·871 per cent. carbon bar.

Stress-Strain Curves.—Reference has already been made in the introductory portions of this Report to the work of MM. Charbonnier and Galey-Aché on the stress-strain curves of annealed iron (page 14). A number of these curves have been taken autographically for the present research, and their salient features will now be described.

The most important feature of a stress-strain curve is that it is possible to determine easily the "yield point," which is often confused with the "elastic limit." In the commercial testing of iron and steel, where only a comparatively rough determination of the elastic limit is required, the figure obtained for the first indications of the "yield point" is generally near enough for all practical purposes.

For the determination of the true "elastic limit," it is necessary to employ an instrument of great accuracy, since "the 'elastic limit' is the stress at which proportionality between the stresses and strains first visibly ceases when measurements of considerable delicacy are being made."* For the "yield point," however, instruments of great delicacy are unnecessary, and the curves given in the Report, which show three times the actual elongation, are sufficiently accurate for most practical purposes. In the testing of iron and steel, it may be taken that the "yield point" is the first large and almost sudden deformation obtained during the testing of the bar.

A recording instrument for taking stress-strain curves is so arranged that the strain or extensions of a test-piece are drawn as abscissæ on the axis of OX, and the stresses in tons per square inch are at the same time drawn as ordinates on the axis of OY, thus forming a curve which gives the relation of stress and strain for the whole test, there being for every increase of stress also a corresponding increase of strain.

A typical stress-strain curve is shown in Fig. 117 (page 74). Up to the point K the line OK is straight, thus indicating that the stress is proportional to the strain, but beyond the point K a slight curvature begins, and a small deviation from proportionality begins to appear in the stresses and strains, so that the point K will indicate the "elastic limit" from the above definition. Frequently this disproportion suddenly becomes more marked at a point L, at which a sudden increase of permanent elongation commences, and this point is generally known as the "yield point," or breaking down point. Between K and L the amount of permanent distortion is extremely slight, but between L and N a small portion of the distortion is elastic, but for the greater part is permanent. In a hard steel possessing but little ductility fracture would occur at N, but in soft ones, in which a considerable reduction of sectional area occurs, a local extension commences which is confined to only a small portion of the bar, and the curve falls rapidly from N to P,

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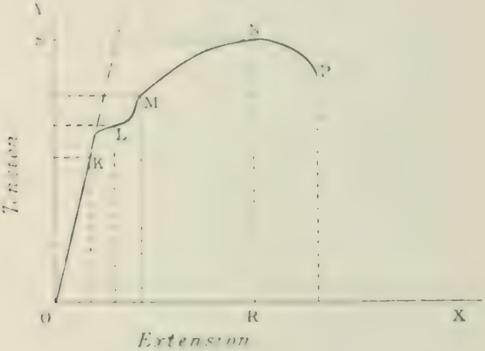
* Unwin, "Testing of Materials of Construction."

FIG. 117.



where fracture occurs. In either case OS indicates the strength of the specimen, as it is doubtful whether any definite relation exists between stress and strain in the curve NP.

A large number of stress-strain curves magnified three times were taken from the bars thermally treated for this Report, and the results obtained from the various series annealed for half-an-hour, and also for those quenched in water, are given on Plates 29 to 33. From the stress-strain curves for the annealed bars it would appear that an annealing immediately below A_1 produces well-defined elongations at the yield points in all bars, except the saturated ones. In the high and low-carbon bars the magnitudes of these elongations both diminish towards the 0·871 per cent. carbon steel, where the yield point is entirely absent. This peculiarity also occurs in the set of bars annealed at 720° C. (1,328° F.), but to a less extent, and in this case the yield point is also absent in the 0·947 per cent. carbon bar.

The yield points of the 800° C. (1,472° F.) annealed bars do not differ greatly in magnitude from those annealed at 720° C. (1,328° F.), but they are, however, much more definite in character, and there is also a slight break in the curve of the 0·871 bar. An annealing at 900° C. (1,652° F.), however, has the effect of obliterating the yield points of the four high-carbon steels, while the low-carbon bars show well-defined "breaks."

In the annealings at 1,100° C. (2,012° F.) the "yield points" of the 0·18, 0·254 and the 0·468 bars have been considerably diminished both in size and regularity, while in the 0·722, 0·871, 0·947 and the 1·306 per cent. bars they are entirely absent.

The curves obtained from the bars quenched in water, as will be seen on reference to Plates 32 and 33, differ to some extent from the curves obtained from the annealed bars. While the bars quenched at 720° C. (1,328° F.) give but little elongation at the yield point, they nevertheless extend considerably immediately before fracture, when the breaking load is applied. This also occurs in the 0·13, 0·18 and 0·254 bars, quenched at 800° C., but the 0·722 and the 1·306 per cent. carbon bars actually show less than 1 per cent. of permanent extension after breaking. Only three satisfactory curves were obtained for the bars quenched at 900° C. (1,652° F.), and they were of the low-carbon steels; the 0·13 bar shows a well-defined elongation at the yield point, and a considerable extension at fracture, but in the 0·18 and the 0·254 bars the yield point is entirely absent. A small amount of permanent extension takes place before fracture only in the 0·18 bar, the 0·254 steel breaking without further elongation on the application of the breaking strain.

Only three low-carbon steel curves were obtained for the 1,200° C. (2,192° F.) quenchings, on account of the rotten state of the high-carbon bars. In none of the curves are there any indications of yield points, and only in the 0·13 bar does a certain amount of permanent elongation immediately precede fracture.

The main conclusions gathered from these curves are:—

(1) The amount and regularity of the elongation at the yield point are dependent on—

- (*a*) The non-homogeneity of the steel. It is always greater when the steel is made up of two constituents—such as: ferrite and pearlite, ferrite and sorbite, pearlite and cementite, and ferrite and martensite—than when it is composed entirely of pearlite, sorbite, or martensite.
- (*b*) The bar being annealed below A_1.
- (*c*) The amount of ferrite present.

(2) The amount of elongation which immediately precedes fracture is dependent on—

- (*a*) The non-homogeneity of the steel, as in the last case.
- (*b*) Other conditions as regards thermal treatment being equal, the bars containing most ferrite show greatest elongation.
- (*c*) It is generally increased by an annealing at 620° C. (1,148° F.).
- (*d*) It is usually absent when the bar is composed of martensite, and is entirely so when "burning" has occurred in the steel.

Miscellaneous photo-micrographs of thermally and mechanically treated steel.—Since it is possible to read the life-history of a piece of steel from suitably prepared photo-micrographs, it has been decided to publish a few of the plates taken for the Committee, all of which are quite typical structures of the steels they represent. The majority of these plates are of steels which have received some special thermal or mechanical treatment under works conditions, and are perhaps the more valuable on this account.

It is well known that specimens of both iron and steel, produced under apparently the same conditions, often display totally different properties. This is especially the case with steel, which, on account of its more complex character, is easily affected by small alterations in the conditions of its manufacture. The causes of the variation in properties of similarly produced samples of metal may, in most cases, be explained by the aid of the microscope when all other methods of investigation have failed. Although it is possible, by means of the microscope, to learn much about the chemical composition of the metal under examination, it is nevertheless not for this purpose that it is most useful. Many samples of steel, having identical chemical composition, vary enormously in mechanical properties; and it is by the aid of the microscope that the causes of these variations may be explained. "Photo-micrography," or, as it is now more frequently termed, "metallography," is intended to augment rather than supplant chemical analysis. It is possible, by means of the microscope, to ascertain much about the mechanical and thermal treatment the metal has received, which in commerce is often of the utmost importance.

Although much useful information may be obtained from low power (say 100 diameter) photographs, yet it is under the higher powers of the microscope (1,000 to 2,000 diameters) that the true effect of tempering or annealing can be ascertained.

The changes in hardness of a steel die, for example, are accompanied by a corresponding change of structure. When the die is quenched in water, its structure, as revealed under the microscope, is composed of a system of interlacing acicular crystallites (austenite, variety martensite). When this steel is tempered, the interlacing crystalline fibres disappear, and the structure becomes granular. The character of the tempered structure varies greatly with the temperature and the time the steel is reheated. In practice, the steel is tempered by watching the colours assumed by the surface of the metal during the progress of the operation, and when the proper colour makes its appearance the object is suddenly cooled. These tints are caused by films of oxide, corresponding with considerable exactitude to the degree of heat to which the metal is exposed, and they consequently serve as a tolerably accurate guide in determining the hardness which the object will acquire on being cooled. Although this method is wonderfully accurate, it must be remembered that the colours will appear even when the metal has not been quenched, so that the tint alone is not indicative of a good result. This may, however, be easily determined under the microscope. As the time and the intensity of the reheating increases, the structure more and more resembles that of pearlite, so that it is quite possible to ascertain the quality of the temper from the micro-structure alone.

To be able to ascertain the quality of the quenching of large masses of metal, such as gun ingots and axles, is of vital importance. If a gun-tube is quenched below the A_1 point, it will be soft and consequently very unsafe for firing purposes, on account of its low elastic limit. Even under the low powers of the microscope valuable evidence could be obtained as regards the correct quenching of the metal, while, under the higher powers, it would be possible to ascertain whether the subsequent tempering had been carried out correctly or not.

In Plates 34 to 39 are shown a number of photo-micrographs, many of which indicate typical structures of thermally treated steels as obtained in practice.

On Plate 34 are shown six photo-micrographs, at magnifications of either 850 or 1,600 diameters, of high carbon steels which have been thermally treated in different ways. Fig. 127 was obtained by quenching a piece of 1·4 per cent. carbon blister steel from 1,050° C. (1,922° F.) in iced brine. The constituents shown are austenite, the white, and cementite, the dark substance. Fig. 128 is a remarkable structure obtained by M. Osmond by placing austenite in liquid air at −243° C. (−469° F.); this structure indicates the transformation of γ iron into the a state. A similar change takes place when certain non-magnetic nickel steels are cooled in a mixture of solid carbon dioxide and ether.

Fig. 129 is a structure obtained when a steel containing 1·4 per cent. of carbon is rapidly cooled in air; it consists mainly of a matrix of incipient pearlite containing large acicular crystallites of cementite. Fig. 130 shows the structure of a "burnt" die which has been quenched in water, at a magnification of 850 diameters. It will be seen to consist of martensite, which is traversed by numerous black lines which have been already described. Such a die could be resuscitated by carefully heating to about 900° C. (1,652° F.) and forging two or three times. Figs. 131 and 132 represent respectively an oil-hardened spring for a safety-valve and an oil-hardened spindle containing 1·02 per cent. of carbon. Both these structures are very good examples of oil hardened high-carbon steels; the pearlite of the spring steel is, however, rather more granular than the spindle.

Plate 35 is interesting, as it shows the structures assumed by gun steel containing 0·33 per cent. of carbon and 0·6 per cent. of manganese, in practice, after different conditions of thermal treatment. Fig. 133 indicates the structure of the original ingot, which has not been reheated. The crystals are bounded by more or less straight lines. In Fig. 134 this structure has been broken up by re-heating the ingot to 900° C. (1,652° F.), forging and allowing it to cool slowly. In this case the boundaries of the crystals are irregular in shape, and have assumed the so-called "interlocked" structure. Fig. 135 was taken from the exterior of the metal after it had been "oil-tempered," that is, the forged tube has been heated to 815° C. (1,500° F.), quenched in oil and afterwards re-heated to 475° C. (887° F.), and allowed to cool slowly. The structure consists of a minute granular pearlite which is traversed by threads of ferrite; these threads increase in size as the centre of the metal is approached. Fig. 136 shows the structure of the carbide area of Fig. 135 under the high power (1,600 diameters). It is composed of a minute granular pearlite. Fig. 137 indicates the interior of the same gun-tube under the low power (140 diameters). In this case the cooling has been slower than it was at the exterior of the tube, and in consequence the separation of the ferrite has been more complete. As would be expected the carbide area in this part of the metal is in a minutely laminated state, not in the granular form in which it exists at the exterior of the tube. This structure is well shown in Fig. 138 at a magnification of 1,600 diameters.

On Figs. 139, 140, and 141, Plate 36, are shown the results of more rapidly quenching a steel of approximately the same composition as the last. Figs. 139 and 140 are the structures obtained at 140 and 850 diameters magnification respectively by quenching the steel in mercury at 720° C. (1,328° F.), and then lightly etching it; in this instance the ferrite has been attacked while the martensite still remains bright, somewhat resembling cementite. In Fig. 141 is shown a portion of one of these martensite patches at a magnification of 1,600 diameters, which has been etched for two minutes in a 0·1 per cent. solution of nitric acid in alcohol; the needle-like structure at once discloses its identity. Fig. 142 is a photo-micrograph of a manganese sulphide flaw in a slowly cooled gun-steel at a magnification of 850 diameters. Fig. 143 is the structure of an ingot of very mild steel which has been allowed to cool after casting; the carbide areas are bounded by straight lines similar to those of the gun ingot in Fig. 133, Plate 35, and, in this case, each grain is also partly surrounded by a layer of free cementite. The metal in this condition was extremely brittle, but on re-heating the steel to 850° C. (1,562° F.), and allowing it to cool in wood ashes, a perfectly malleable ingot was the result. The structure given by this reheated metal is shown in Fig. 144. Both Figs. 143 and 144 are at magnifications of 140 diameters.

Plate 37 is an interesting one, as it indicates the variation of the structure in different parts of a 10-inch axle containing 0·4 per cent. of carbon which has been oil-tempered. The photo-micrographs are not very good, but they nevertheless show a large proportion of carbide area at the exterior of the axle, and a gradually diminishing amount in the sections as they approach the centre, while at the centre the structure is practically that of a slowly cooled steel. An excellent series of photo-micrographs of axles were taken at the Royal Mint, but after Sir William Roberts-Austen's death they could not be found. In every case, however, the structures varied from exterior to centre in the manner indicated on Plate 37. Such a heterogeneous structure must entail a considerable amount of internal strain, even under the best conditions of oil-quenching; and it therefore appears advisable to seek for other means of obtaining a metal with suitable properties, such as, power of withstanding "shock," while at the same time possessing comparatively high limits of elasticity and tenacity. These properties can, without doubt, be obtained in slowly cooled steels containing a small proportion of one or more of the rare metals, and it is possible that equally good results may be obtained with suitably annealed carbon steels.

Plate 38 is of particular interest. Figs. 151, 152, 153, and 154 show the structure, under different magnifications, of the "cutting edge" of a cast-iron tool which the Secretary brought from the locomotive workshops of the Pennsylvania Railroad Company in Altoona, and handed to the Committee. All these photo-micrographs show that the metal is composed of a large quantity of cementite embedded in a matrix of a dark substance which, at a magnification of 1,600 diameters, Fig. 154, shows the presence of a very minute form of pearlite in conjunction with martensite.

This metal would seem to be suitable for high-speed lathe work. The ordinary tool when used for high-speed work rapidly becomes dead soft by "tempering," on account of the heat produced, while a self-hardening tool in most cases rapidly loses its edge. Cementite, on the other hand, is quite unaltered at temperatures of even 600° C. (1,112° F.) or 700° C. (1,292° F.), so that a good cast-iron tool will retain its edge for some considerable time.

Figs. 155 and 156 show two spindles, one of which gave exceedingly good results, while the other gave very poor ones as regards wear. The total carbon in each spindle was approximately the same, viz., 1·45 and 1·50 per cent. respectively. A determination of the graphitic carbon, however, revealed the fact that, whereas Fig. 155 did not contain any, Fig. 156 contained 0·22 per cent. On reference to the photo-micrographs it will be seen that, while the bad spindle is entirely composed of granular pearlite, the good one contains a considerable amount of cementite, and it is entirely due to the extremely hard bearing surface, presented by the cementite patches, that the good lasting qualities of this spindle are due. It is interesting to note that many good bearing metals owe their qualities to a similar cause; the metal is generally composed of a comparatively soft matrix containing some hard metallic compounds which form the bearing surface, in the same way that the cementite does in the spindle.

Fig. 157, Plate 39, shows the structure of a steel containing 0·4 per cent. of carbon, which has been heated to about 900° C. (1,652° F.) and quenched in mercury, thus producing well-developed martensite. The sample was then placed in an oven at 100° C. (212° F.) and allowed to remain there for 1,500 hours. Fig. 158 indicates the structure produced by this treatment, and it will be observed that it is very similar to that obtained from a water-quenched steel which has subsequently been tempered to a straw colour under normal conditions.

Figs. 159 and 160 show the structures of a piece of steel containing 0·8 per cent. of carbon which has been burnt and then slowly cooled. The photo-micrographs are at magnifications of 140 and 850 diameters respectively. It will be observed that black furrows and spaces exist in the slowly cooled as in the quenched ones. The two remaining structures on the Plate were produced by mechanical treatment. Fig. 161 is from a rail containing 0·5 per cent. of carbon and about 0·8 per cent. of manganese. The section was prepared from the "running edge" of the rail, and the effects ot the "cold rolling" can be plainly seen. In Fig. 162 is shown the effect of strain on tool steel in the soft condition. A small section was removed from the tool and polished, but was neither polished in relief nor etched. The sample was then placed in a small testing machine and gently squeezed. On examination it was found that a pearlite structure had developed, owing to the ferrite laminae being forced up between the plates of cementite.

The matter contained in this Report by no means represents the total work done for the Alloys Research Committee, as much time was given to experiments which yielded negative results.

In conclusion, attention should again be drawn to the valuable work of Mr. W. H. Merrett, who has supplied the material for the completion of the Report, and for which he deserves the special thanks of the Committee.

Their thanks are also due to Messrs. F. W. Harbord and P. Reilly, of the Royal Indian Engineering College, to whom were entrusted the analyses of the specimens of steel and the determination in most cases of their mechanical properties after thermal treatment, and who have spared no efforts to ensure the trustworthiness of the results; and to Mr. S. W. Smith, B.Sc., of the Royal Mint, who assisted in some of the experimental work.

The Report is illustrated by Plates 1–39.

TABLE 21.

Comparison of Breaking Strains (in tons per square inch) of Annealed and Soaked Bars.

Carbon per cent.	Original bars as received.	Bars annealed for Half-an-hour.					Bars soaked for Twelve Hours.			
		620° C. (1148° F.)	720° C. (1328° F.)	800° C. (1472° F.)	900° C. (1652° F.)	1100° C. (2012° F.)	620° C. (1148° F.)	720° C. (1328° F.)	900° C. (1652° F.)	1200° C. (2192° F.)
0·130	30·22	—	20·16	20·10	21·48	—	19·75	20·00	—	—
0·180	31·52	30·60	26·52	26·46	27·84	26·91	26·81	27·75	26·91	25·27
0·254	33·25	34·50	28·80	29·40	29·46	28·11	28·61	28·18	29·55	24·86
0·468	36·96	37·02	32·82	33·00	32·46	31·38	32·01	29·31	29·91	29·10
0·722	49·00	50·22	39·96	42·48	43·20	42·38	40·63	38·11	43·21	40·17
0·871	58·02	55·02	43·98	52·50	50·40	47·69	45·25	39·39	49·32	29·55
0·947	53·74	52·90	39·30	39·96	51·12	49·62	45·41	33·73	47·76	24·02
1·306	56·11	51·54	50·58	39·12	44·52	46·62	46·96	33·38	44·41	35·93

TABLE 22.

Comparison of Elastic Limits (in tons per square inch) of Annealed and Soaked Bars.

Carbon per cent.	Bars annealed for half-an-Hour.					Bars soaked for Twelve Hours.			
	620° C. (1148° F.)	720° C. (1328° F.)	800° C. (1472° F.)	900° C (1652° F.)	1100° C. (2012° F.)	620° C. (1148° F.)	720° C. (1328° F.)	900° C. (1652° F.)	1200° C. (2192° F.)
0·130	—	11·34	10·20	13·02	—	10·64	11·67	—	—
0·180	26·50	14·52	16·08	15·84	15·37	14·31	7·63	20·62	20·76
0·254	27·78	18·24	19·44	17·28	15·30	17·22	15·81	25·09	17·00
0·468	27·36	21·60	18·72	18·03	14·28	22·08	11·76	25·58	23·79
0·722	31·68	22·98	†	†	†	21·13	16·16	38·74	29·91
0·871	29·28	†	†	†	†	21·96	15·28	42·75	21·65
0·947	34·20	†	22·50	†	†	23·15	14·11	36·07	20·09
1·306	40·92	†	†	†	†	28·29	11·69	38·04	26·77

† No definite yield point.

TABLE 23.

Comparison of the Elongations per cent. on 2 inches of Annealed and Soaked Bars.

Carbon per cent.	Original bars as received.	Bars annealed for Half-an-hour.					Bars soaked for Twelve Hours.			
		620° C. (1148° F.)	720° C. (1328° F.)	800° C. (1472° F.)	900° C. (1652° F.)	1100° C. (2012° F.)	620° C. (1148° F.)	720° C. (1328° F.)	900° C. (1652° F.)	1200° C. (2192° F.)
0·130	20·00	—	44·50	46·20	45·00	—	48·50	42·50	—	—
0·180	12·50	33·00	36·00	35·00	33·50	39·50	32·50	29·50	37·00	18·00
0·254	12·70	24·00	32·50	29·50	32·50	33·50	31·00	31·00	29·00	12·50
0·468	6·25	24·00	29·00	27·50	28·00	27·00	33·00	30·50	30·00	16·00
0·722	11·72	20·50	23·00	17·70	16·50	14·00	29·50	21·00	12·50	11·00
0·871	5·47	12·00	20·00	11·50	11·20	11·00	19·50	19·50	11·00	20·00
0·947	7·03	15·00	22·00	18·00	10·00	7·50	18·50	23·50	11·90	20·00
1·306	7·03	*3·00	7·00	20·00	5·50	6·50	11·50	26·50	10·00	33·00

* Broke outside gauge points.

TABLE 24.

Comparison of the Reductions of Area at Fracture (in Percentages) of Annealed and Soaked Bars.

Carbon per cent.	Original bars as received.	Bars annealed for Half-an-hour.					Bars soaked for Twelve Hours.			
		620° C. (1148° F.)	720° C. (1328° F.)	800° C. (1472° F.)	900° C. (1652° F.)	1100° C. (2012° F.)	620° C. (1148° F.)	720° C. (1328° F.)	900° C. (1652° F.)	1200° C. (2192° F.)
0·130	34·73	—	73·26	71·16	71·16	—	81·12	73·21	—	—
0·180	29·71	62·85	72·54	67·32	60·24	60·60	71·43	61·11	58·80	59·30
0·254	25·31	55·06	62·66	58·56	54·84	54·77	65 18	57·28	57·50	56 80
0·468	18·76	49·70	58·56	45·60	46·26	40·38	57·61	42·70	43·50	38·80
0·722	3·43	33·48	47·88	31·71	25·86	17·21	46·54	35·97	11·00	11·30
0 871	5·38	22·11	40·42	16·92	15·84	12 51	30·82	29·69	15·30	40·20
0·947	5·63	27·00	45·00	28·44	15·42	9·07	27·10	35·44	11·00	37·50
1·306	8·48	3·90	5·12	33·90	5·58	8·94	16·45	34·50	11·70	21·70

TABLE 25.

Comparison of Breaking Strains (in tons per square inch) of Bars Quenched in Water and in Oil.

Carbon per cent.	Original bars as received.	Quenched in Water at 20° C. (68° F.).				Quenched in Oil at 80° C. (176° F.).					
						Not tempered.	Tempered at 350° C. (662° F.).			Tempered at 600° C. (1112° F.).	
		720° C. (1328° F.)	800° C. (1472° F.)	900° C. (1652° F.)	1200° C. (2192° F.)	720° C. (1328° F.)	720° C. (1328° F.)	870° C. (1598° F.)	1000° C. (1832° F.)	800° C. (1472° F.)	900° C. (1652° F.)
0·130	30·22	36·18	38·88	32·34	45·29	32·68	22·13	24·50	25·91	21·42	24·55
0·180	31·52	44·82	49·02	49·92	72·78	36·79	31·10	36·12	35·96	36·16	30·13
0·251	33·25	43·20	52·38	70·32	77·04	37·84	34·15	41·13	40·32	—	31·24
0·468	36·96	39·60	61·26	55·44	31·74	39·75	41·83	51·65	51·10	41·06	35·71
0·722	49·00	51·00	*	61·98	13·44	50·43	48·70	78·59	76·41	58·47	50·44
0·871	58·02	54·84	*	26·04	5·40	76·77	53·94	90·68	83·84	53·11	52·68
0·947	53·71	56·04	*	21·60	4·20	52·30	54·63	102·52	94·19	45·97	49·10
1·306	56·11	56·94	70·02	*	3·52	53·82	57·75	90·57	90·00	46·86	51·32

* Broke in clips.

TABLE 26.

Comparison of Elastic Limits (in tons per square inch) of Bars Quenched in Water and in Oil.

Carbon per cent.	"Normalised" Bars. Annealed at 620° C. (1148° F.)	Quenched in Water at 20° C. (68° F.).				Quenched in Oil at 80° C. (176° F.).					
						Not tempered.	Tempered at 350° C. (662° F.).			Tempered at 600° C. (1112° F.).	
		720° C. (1328° F.)	800° C. (1472° F.)	900° C. (1652° F.)	1200° C. (2192° F.)	720° C (1328° F.)	720° C. (1328° F.)	870° C. (1598° F.)	1000° C. (1832° F.)	800° C. (1472° F.)	900° C. (1652° F.)
0·130	—	†	†	24·30	†	18·67	11·89	15·69	19·62	19·78	15·62
0·180	26·50	†	†	†	†	24·24	16·83	23·81	23·42	29·82	24·55
0·254	27·78	†	†	†	†	24·94	22·56	28·81	25·29	—	25·89
0·468	27·36	†	†	†	†	29·14	25·43	42·52	37·24	31·92	29·02
0·722	31·68	†	*	†	†	30·74	27·47	36·54	59·96	49·90	44·63
0·871	29·28	†	*	†	†	50·24	27·38	67·55	58·30	46·86	46·85
0·947	34·20	†	*	†	†	40·00	36·52	66·73	68·13	35·70	40·18
1·306	40·92	†	†	*	†	37·75	40·13	56·29	59·81	42·50	42·40

* Broke in clips. † No definite yield point.

TABLE 27.

Comparison of the Elongations (per cent. on 2 inches) of Bars Quenched in Water and in Oil.

Carbon per cent.	Original bars as received.	Quenched in Water at 20° C. (68° F.).				Quenched in Oil at 80° C. (176° F.).					
						Not tempered.	Tempered at 350° C. (662° F.).			Tempered at 600° C. (1112° F.).	
		720° C. (1328° F.)	800° C. (1472° F.)	900° C. (1652° F.)	1200° C. (2192° F.)	720° C. (1328° F.)	720° C. (1328° F.)	870° C. (1598° F.)	1000° C. (1832° F.)	800° C. (1472° F.)	900° C. (1652° F.)
0·130	20·00	22·00	21·70	28·20	9·00	26·00	41·00	39·50	32·50	38·00	40·70
0·180	12·50	14·00	14·50	6·50	3·50	25·00	29·00	23·50	26·50	26·00	30·00
0·254	12·70	13·70	6·50	3·80	3·00	23·00	25·00	24·50	19·00	—	26·20
0·468	6·25	21·00	1·00	1·00	Nil	21·50	20·00	25·00	14·00	17·00	27·20
0·722	11·72	17·50	*	1·00	Nil	16·50	21·50	23·50	14·00	17·50	17·50
0·871	5·47	15·80	*	2·00	Nil	13·00	13·50	10·50	9·50	15·00	15·50
0·947	7·03	12·00	*	Nil	Nil	13·00	12·00	7·00	5·50	12·00	17·00
1·306	7·03	8·80	0·50	—	Nil	7·00	6·50	5·50	5·00	7·50	13·00

* Broke in clips.

TABLE 28.

Comparison of the Reductions of Area at Fracture (in Percentages) of Bars Quenched in Water and in Oil.

Carbon per cent.	Original bars as received.	Quenched in Water at 20° C. (68° F.).				Quenched in Oil at 80° C. (176° F.).					
						Not tempered.	Tempered at 350° C. (662° F.).			Tempered at 600° C. (1112° F.).	
		720° C. (1328° F.)	800° C. (1472° F.)	900° C. (1652° F.)	1200° C. (2192° F.)	720° C. (1328° F.)	720° C. (1328° F.)	870° C. (1598° F.)	1000° C. (1832° F.)	800° C. (1472° F.)	900° C. (1652° F.)
0·130	34·73	60·20	59·94	76·26	35·12	59·62	75·91	76·44	67·48	70·60	72·00
0·180	29·71	46·92	51·60	35·28	5·16	60·24	59·88	65·38	63·04	57·00	58·50
0·254	25·31	45·96	8·94	13·44	4·74	57·77	57·87	62·14	60·51	—	58·40
0·468	18·76	48·78	6·00	2·64	Nil.	48·82	50·12	47·17	63·59	52·30	51·00
0·722	3·43	32·92	*	2·56	Nil.	36·54	36·00	38·08	32·69	38·90	33·30
0·871	5·38	29·58	*	2·16	Nil.	36·34	27·63	31·82	24·15	32·60	30·00
0·947	5·63	24·78	*	Nil.	Nil.	19·81	18·64	16·99	14·84	12·90	28·00
1·306	8·48	15·84	1·32	†	Nil.	8·67	—	10·57	7·09	22·00	21·00

* Broke in clips.

† Broke outside gauge points.

Discussion on 15th January 1904.

The **President** remarked that they had just listened to the Sixth and concluding Report of a series started by the Institution in 1889. That series of researches had therefore been going on for fourteen years, and the research incorporated in the present Report had been progressing for about five years, because, although only three years had elapsed since the Fifth Report was presented, the work done as detailed in the present Report began before the previous one was completed. It would have been noticed that the beginnings of the discoveries elucidated in that Report had been traced back 120 years, beginning with Bergman in 1781, and the scope of the Report was set forth in the following passage (page 9): "It is now known that allotropic changes in the iron itself are the all-important factors in determining the relations between iron and carbon, which are involved in the characteristic capacity of steel for being hardened and tempered. If iron had existed only in the α form, it could never have been hardened by quenching; on the other hand, if β and γ iron were alone known, steel could never have been tempered or annealed. The prevalent belief, therefore, of nearly two centuries, which claimed attention for the carbon alone, has had to be abandoned. Bergman, in 1781, held the first links of evidence which have led to the present conclusion, while Osmond, in the last decade, has forged the strong and important portion of the chain which we securely hold. In the future it will be realised how much the Institution of Mechanical Engineers has done to confirm, strengthen and diffuse the knowledge we possess on the important industrial question of hardening steel." Those were the words of Sir William Roberts-Austen himself. The thanks of the Institution for that masterly Report were due to the late Sir William Roberts-Austen and to his successor in the Chair of Metallurgy at the Royal School of Mines, namely, Professor William Gowland, and he thought the Members would wish him to express on their behalf their appreciation of the ability, perseverance, and enthusiasm with which Mr. Merrett had carried out the large amount of work which it had been his duty to do in that research. The names of honorary workers, Mr. F. W. Harbord, Mr. S. W. Smith, Mr. P. Reilly, and others were mentioned by Professor Gowland in the Report. The Institution thanked those gentlemen. All that co-operation illustrated the power of Sir William Roberts-Austen to attract other minds, and of that, one found further evidence during the last few days, when the Institution had received contributions to the subject from Professor Ledebur and Professor Le Chatelier, who he was pleased to see was present, and the meeting would have the pleasure of hearing him soon, perhaps in his own native tongue. The Committee also who had stimulated those researches were to be congratulated on the valuable results which had been brought about. With that Committee it was desired to associate the names of the late Sir William Anderson and the present Chairman, Sir William White, Sir Edward Carbutt and the late Sir Frederick Bramwell, all Past-Presidents of this Institution.

The thanks of the Institution to those gentlemen were manifested by hearty applause.

Professor GOWLAND said he feared he must not detain the meeting with any remarks supplementary to the very long Report, but he would like to call attention to the series of photographs exhibited on the walls. They were between 75 and 80 in number, and had been arranged to show the work of his old friend Sir William Roberts-Austen, the work which he did for the Alloys Research Committee of the Institution. Those photographs were about to be sent to the St. Louis Exhibition, where they would be exhibited by the British Committee of Mining and Metallurgy to illustrate the work of Sir William Roberts-Austen and of the Institution of Mechanical Engineers.

Professor HENRY LE CHATELIER, speaking in French, said that he had read with much interest the Sixth Report to the Alloys Research Committee. The accurate manner in which the experiments had been made and the lucid way with which they had been set forth were beyond question, and the Report constituted a collection of data which would form an invaluable source of knowledge for future inquiries in this field of scientific research.

Before proceeding to details, he thought it might be of interest to consider the influence of the Report in a wider sense than that of immediate application. In metallurgical science, as in other kindred branches of philosophical inquiry, unsuspected problems would arise, and these became more numerous as the ramifications of the science extended. Thus, after having recognised the attraction of a piece of resin rubbed on cloth for light bodies, one might hope, by further experiment, to gain a more complete knowledge of the phenomenon. To-day the whole science of electricity was founded on this first observation, though it had been necessary for centuries to pass before the science became fully organised. It was reasonable to hope for a more rapid development of metallurgical science, and it was the duty of workers in this field to prepare for the higher development.

An error frequent among savants was to seek to arrive at truth by too many roads, without taking thought of the ground to be covered. This was to ignore the value of time and the waste labour of retracing steps. He would appeal to technical societies, such as this Institution, to oppose energetically such practice of this nature. The Institution of Mechanical Engineers had rendered signal service to metallurgy by the formation of the Research Committees and by the publication of their Reports; and the example had been followed elsewhere. He had proposed to the Société d'Encouragement pour l'Industrie Nationale the formation of an Alloys Committee, and it was with the help of the late Sir William Roberts-Austen that he had been able to meet the first difficulties inseparable from the founding of an organisation of this nature. Sir William had desired to visit Paris in order to submit his first Report to the Société, and to compete for one of its prizes. Such a step would have given the speaker the pleasure of introducing to his French colleagues the efforts made on the other side of the Channel to advance the science of Metallurgy. It would not be out of place to remind the meeting that the Société d'Encouragement pour l'Industrie Nationale had been modelled on the Society of Arts in London, having been founded by Lasteyrie in 1754, upon his return from a visit paid to England. Such international relations were of great value in promoting science and industry.

The progress of science might be divided into two distinct stages: the first period was one of creation; the second was that of progressive development. In the first there was no organization: no richly equipped laboratories were needed; they would be injurious. Boyle and Mariotte would not have discovered the laws of compressibility of gases, if they had had at their disposal the improved apparatus of Regnault. By watching a lamp swing, Galileo discovered the law of weight, and Newton, by observing an apple fall to the ground, discovered the laws of gravitation.

Directly the second period was entered upon, more minute inquiry was needed, for the complexity of aspect of each phenomenon became every day more marked. To achieve this progress, it was not sufficient to make experiments and tests, but to make them on useful subjects. One might mention as an example of wasted labour—the making of thousands of hygrometrical experiments with unsuitable apparatus. In that case a good organization would have been extremely advantageous.

The question of the thermal treatment of steel was certainly of primary importance; but, he would ask, would it not be necessary in the future to apply other tests besides tensile tests? Such tests answered the purpose of showing the difference of the properties of steel when heated from 800° C. (1,472° F.) to 1,200° (2,192° F.), or between a steel heated for a quarter-of-an-hour or for ten hours. But if it were necessary to know the influence of a change of 50° C. at high temperature or the prolongation of heating for a quarter-of-an-hour, mechanical tests were not to be relied upon. The errors resulting from small differences between test-bars completely disguised the results; nevertheless, the small differences of treatment mentioned had most important influences on the nature of the steel. A much more useful method of testing was that by means of notching bars. In illustration of this, he instanced tests made by M. Guillery, director of the Société Française de Construction

Mecanique à Denain. A bar of mild steel with a breaking strain of 38 kg. per square millimètre (24·13 tons per square inch) and 34 per cent. elongation was divided into three parts, and from each a test piece was cut so as to judge of the homogeneity. The three parts were heated to 900° C. (1,652° F.), and tempered at 600° C. (1,112° F.). One of these was put aside, and the two others were brought to a white heat—one for a quarter-of-an-hour, and the other for half-an-hour. The following tests were made:—(1) Simple tensile tests with apparent raising of the elastic limit; (2) Continuous bending tests by rotation (Wohler's tests); (3) Tests on notched bars. The following Table gave the results of the tests:—

TABLE 29.

	Simple Tensile Tests.			Flexion tests by continuous rotation.	Fremont test with rectangular notched bars.
	Breaking Strain per mm².	Apparent Elastic Limit.	Elongation per cent.	No. of Turns before rupture.	Kilogram-metres absorbed
Steel untreated . .	37·7	13·3	31·2	—	—
Steel hardened and tempered . . .	38·0	13·3	35·0	175	32
Steel heated to 1,200° C. for ¼ hour . .	38·6	7·3	28·5	123	20
Steel heated to 1,200° C. for ½ hour . .	38·6	5·3	29·0	70	1

The tensile tests and the elongation gave no indication of the effect of heat in causing deterioration of the metal, whilst the trials by notched bars gave this very clearly. In bringing forward these instances he dwelt on the necessity of a good programme being arranged for investigations of this nature, and it was therefore most desirable to submit any scheme to public discussion.

(Prof. H. Le Chatelier.)

Experimentalists were liable to make mistakes, and industrial questions were more difficult to solve that those of pure science. The only method was for the same problem to be studied by experimentalists independently in various countries. Considerable experience had already been obtained on the thermal treatment of steel by Brinell and Wahlberg, by Professor Arnold, Dr. Campbell, and by the Alloys Research Committee of this Institution. Although the majority agreed fairly well in their general lines, yet there were certain points of difference. Was it better to temper steel rapidly to 900° C. (1,652° F.) or to keep it several hours at that temperature? That was a point to take up again, since results did not agree. One could not tell if these discrepancies occurred through experimental errors or through the different quality of the metals experimented upon. One of the objects to be aimed at should be co-operation among seekers of knowledge. It was difficult to estimate the amount of wasted efforts in the laboratories of the world through this want of co-operation. It was enormous compared with that of industrial work. It was only within the last five-and-twenty years that any considerable movement had taken place in metallurgical study; some new methods have been adopted, but only on a very feeble foundation.

The work of Sorby and of Osmond had opened some new paths in the study of alloys, and every day numerous experimenters were following on the same road. Some considerable progress ought to have been made, in view of the enormous mass of literature that had been accumulated. It was a mere trifle though; obscurity was met with everywhere, when it ought to be clearness which was the characteristic of every well-established science. Micrography was hardly accessible to the majority of engineers; and those experimenters who pursued the subject did not agree with each other. For instance, in the Report (page 54) it was stated that there was martensite in a steel tempered at 720° C. (1,328° F.); that would be below the points of transformation. Nevertheless the metal remained malleable in a manner inconsistent with the presence of the constituent element of tempered steel. Some metallurgists would join issue on this statement. In a recent Paper on nickel-steels M. Guillet had described as hardenite some crystals that M. Osmond would without doubt have called sorbite, but which he (M. Le Chatelier) would have called troostite. There was a large field of study to cover before the characteristic properties of martensite, hardenite, troostite, and sorbite with their progressive change to pearlite were defined. Above all, it was particularly necessary that the researches of experimenters should run on parallel lines.

Gore, Barrett, and Osmond had opened a new field of important study when they discovered the allotropic transformation of iron and steel, and in this direction knowledge had advanced but little, in spite of the numerous treatises that had been produced. How was it that martensite non-magnetic above the point of transformation became magnetic at the ordinary temperature? Was the transformation of α iron into β iron, accompanied by loss of magnetism without any appreciable change of volume, an allotropic transformation analogous to that of β iron into γ iron? Was the transformation of the magnetic variety of nickel to the non-magnetic comparable with the transformation of α iron to β iron, or was it not rather related to the direct transformation of α iron to γ iron.

He had already shown that the constitution of alloys was the immediate result of the ordinary laws of solubility; solidification took place in the formation of crystals enclosed finally in a eutectic. The Research Committee had made a considerable advance in the theory of the constitution of steel, but one hardly knew anything on the curve of solubility of cementite and graphite in the liquid casting. These examples related exclusively to the elementary phenomena of a study relatively very simple. When one saw all that remained to be done, the uncertainties of such a complex subject as the thermal treatment of steel were readily explained. Very slight variations in the temperature of annealing and in the rapidity of the change in temperature were able to alter the result entirely. To fill up rapidly all the gaps in the knowledge of this subject required the hearty assistance of all interested in progress.

Mr. F. W. HARBORD said he would have preferred to reserve his remarks until a later period of the discussion when possibly he might have been able to deal with some of the criticisms of other speakers. As one of Sir William Roberts-Austen's oldest students, he would

(Mr. F. W. Harbord.)

like to bear testimony to the great work his former master had done for metallurgical science. He had had many discussions with the late Sir William Roberts-Austen in reference to this research, and in the original scheme drawn up it was arranged to carry out a series of experiments on bars of large dimensions. The experiments on the small bars recorded in the Report were only intended as pioneer experiments, and it had been intended to confirm and amplify the results obtained by experiments on a considerably larger scale. He had been making arrangements to carry out these large-scale experiments when the unfortunate illness, followed by the lamented death of Sir William, prevented them from being proceeded with. On referring to Table 2 (page 26) it would be noticed that, on heating the bars to 620° C. (1,148° F.) for half-an-hour, the ratio of elastic limit to the maximum stress was extremely high, and it was intended to have repeated this experiment with another set of bars; but, unfortunately, all the bars had been used for the other experiments. When he saw the results in the Report he immediately made a search and found a few bars of rather smaller section of the same steel; although there was not a complete set, there were some low-carbon steels which were the most important. Some of these were heated at 620° C. and some at 680° C. (1,256° F.), that is, at a temperature intermediate between 620° C. (1,148° F.) and 720° C. (1,328° F.) and the results were given in Table 30 (page 138). Some of these bars were tested at Coopers Hill, and duplicates had been kindly tested by Professor Unwin. It would be seen that although there were slight differences, considering the smallness of the bars, they agreed within reasonable limits, and, at all events, so far as elastic limit was concerned, completely confirmed the results given in the Report.

Since these experiments had been begun the results of a very elaborate series of experiments had been published by Brinell in a Paper by Mr. Wahlberg before the Iron and Steel Institute in 1902 * on the Heat Treatment of Steel; and, had these been published earlier, there was no doubt that the scheme of the present

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* Journal, Iron and Steel Institute, 1902, I, page 333.

research would have been considerably modified; but many of the experiments had by that time been completed. He had very carefully compared the results obtained by Brinell and those recorded in the Report, and after making reasonable allowance for difference in the composition of the steels and difference in the temperature of heating, the results as regards annealing were in very close agreement. The same might be said as to the oil-quenching results, as it would be noticed that there was an increase in the maximum stress the same as produced by water quenching but without a decrease in the elastic limit, which was exactly what Brinell found. Again, both Brinell's and these experiments showed that, as the temperature of quenching was increased, the elastic limit increased; but the elongation decreased, and this was especially marked in the high-carbon steels. He would also call attention to the Paper read by Professor Arnold before the Institution of Civil Engineers,* when it would be seen that the bars heated for half-an-hour to 900° C. (1,652° F.) gave very similar results to those obtained by Professor Arnold on heating to 1,000° C. (1,832° F.), although the former were somewhat softer owing to their being slowly cooled in the muffle instead of in the air, as in the case of the latter experiments. In a Paper read before the Iron and Steel Institute last year by Mr. Campion,† for which he was awarded the Carnegie gold medal, results of heating large bars 4 to 6 inches in diameter showed that the best temperature for annealing steel with carbon up to 0·20 per cent. was from 700° (1,292° F.) to 800° C. (1,472° F.), and this was somewhat at variance both with Brinell's and results given in the Report; and, until the matter had been further investigated by working with large sections, the results obtained with the large sections must be accepted as the correct ones. Although the experimental work recorded was far less complete than Sir William Roberts-Austen intended, he thought it would be found most useful as pioneer work for further research. [*See also page* 137.]

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* Proceedings, Institution of Civil Engineers, 1895–6, vol. cxxiii, page 127

† Journal, Iron and Steel Institute, 1903, I, page 578.

Professor THOMAS TURNER said he wished in the first place to take the opportunity of expressing his regret—and he was sure it was the regret of all present that evening—that Sir William Roberts-Austen was not with them to read his Report. Speaking as one of his old students—for he joined the School of Mines before the end of Dr. Percy's time, and was with Professor Roberts-Austen for two years—he desired to bear testimony to Roberts-Austen's wide scholarship and at the same time his wonderful clearness of vision so far as the important points of any research were concerned. He had an opportunity of speaking to Sir William shortly before his death, when he was suffering severely from the illness which afterwards proved fatal. They were discussing together the advances which had recently been made in metallurgical science, and Sir William said he had done what he could to advance knowledge in that respect, and he hoped that some of that which he had accomplished would remain. He, Professor Turner, felt sure that if Sir William Roberts-Austen had contributed only those six Reports which had been submitted to the Institution, he would have left behind him a monument of which any scientific man might well feel proud. His interests were many-sided, and there was scarcely any branch of metallurgy which was not enriched by his labours at some time or other during his life. It might be said that their deceased friend had helped to discover many of the foundation stones which had been built into the fabric of their science, and upon these others would in future build. One could not expect that a Report of the present kind would be perfect, or that no other researches would be required in order to elucidate the matter. All of them might not agree with every conclusion at which Sir William Roberts-Austen had arrived; at the same time one should be none the less ready to acknowledge the disinterestedness with which he had approached the subject.

He, Professor Turner, had been writing, during the last week or two, a short Paper on the semi-fluid state of metals, and when he received the present Report a day or two ago, he felt sorry that that Report had not been before him whilst he was writing his Paper. The introduction to the Report was only another example of Sir

William Roberts-Austen's clearness of vision. On page 11 would be noticed a reference to the work of Barus, in which he stated "that during the small interval of time within which appreciable annealing occurs, a glass-hard steel rod suddenly heated to 300° C. (572° F.) is almost a viscous fluid." Sir William Roberts-Austen had called attention to facts of that kind on several previous occasions, and in that Report he made reference to other authorities. That portion of the Report called attention to a subject which ought not to be neglected, namely, that in considering the changes which take place in iron and steel one had not only to deal with the condition of the carbon, but also with the viscosity and other qualities of the metal itself. Whether metallurgists were agreed as to the exact details of the allotropic theory or not, they must all recognise that there were very important changes in the structure and character of the iron, by whatever terms they might describe them. He therefore suggested that a great deal of the discussion which had taken place as to the accuracy or otherwise of the allotropic theory was largely a question of definition, and of understanding of terms, rather than a difference of opinion on the real facts which were involved.

He wished to make reference to only one other matter, namely, the diagram on Plate 3. He was very pleased to see that that was brought up to date, as that particular diagram, perhaps, contained more information than any other single one in the Paper. It would well repay a considerable amount of study, and further information would be necessary before some important points were fully explained. He wished to draw attention, however, to the fact that in the Report one had the terms "hypo-æolic," "hyper-æolic," and those terms were also used by Professor Howe in his book recently published—quite a standard work, as those who had seen it would recognise—on Iron, Steel, and other Alloys. But Professor Howe had a note on the last page saying that if he had an opportunity of writing the book again he would use the term "eutectoid." * He thought that a very happy term. Professor Howe had coined a number of words in metallurgy, and he thought the new

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* This word is now employed on Plate 3.

term "eutectoid" was as happy as any, and a useful addition to the nomenclature of the subject. In conclusion, he wished to thank Professor Gowland, and those who were associated with him, for the information they had brought forward.

Dr. R. T. **Glazebrook** said he was glad to rise, simply to re-echo some of the sentiments which had been uttered by Professor Turner as to the indebtedness of all who were interested in metallurgy to Sir William Roberts-Austen and to his co-workers in the Institution, for the great work they had done in the production of those six Reports of which the present was the last. He desired also to express his own regret and that of all Sir William Roberts-Austen's friends that he was not with them to hear the appreciation with which the work had been received. He, Dr. Glazebrook, gathered from what had already been said that there were numerous points connected with that research still needing elucidation and further experiment, and he trusted it might be his good fortune, as Director of the National Physical Laboratory, to help those of his assistants who were working at the subjects to continue and carry out some of the researches and investigations which were outlined in the Report. He wished the President and the members of the Institution to understand that, if those who were directing the National Physical Laboratory could help in this manner, they would be only too pleased to do so, and they would look to that body, the members of which were so well able to afford guidance, as to the particular points to which it was desirable that attention should be directed.

Mr. C. E. **Stromeyer** said he wished to join the previous speakers in their expressions of regret that Sir William Roberts-Austen was not with them, and also to give utterance to his gratification at the large amount of information contained in the Report, and the enormous amount of work which had been bestowed upon these researches. He had one slight criticism to offer on a point to which Professor Le Chatelier had already drawn attention, namely, that the tests on the materials were not as diversified as one would have liked them to be. In addition to the bending tests which Professor Le Chatelier mentioned, he thought that in future researches on this and allied subjects torsion tests should be included, for they gave valuable information on the shearing strength of materials. He was in fact surprised that that test was not included in this inquiry which dealt largely with gun steels, because the bursting of a gun was due to shearing stresses not to tension stresses. He heard with pleasure that there had been a proposal to lengthen the test pieces; that would have been a great benefit, as the real elastic limit could then have been determined with greater precision, in fact, short as the test pieces were, this limit should have been determined.

In some researches which he had carried out, he noticed that the quenching of very mild steel reduced the elastic limit, whereas, with high-carbon steels quenching raised the elastic limit. He wished also to add that he was very sorry to hear that the present was the concluding Report. After what had been said by Dr. Glazebrook, he almost wished that the Research Committee could have been continued, if only for the purpose of giving the desired advice and guidance for which Dr. Glazebrook asked. What constructive engineers were really anxious for was, not so much the qualities of precious metal alloys and of the high-carbon steels, such for instance as were used in guns and stamping dies, but the causes of the effects which heating and other manipulations had on the milder qualities of steel; now that the last two Reports had reached carbon steel, the foundation had been laid for such inquiries. Only quite recently he had a case where some steel, which had admirably stood the bending tests (it bent double) and the usual mechanical tests, broke while in the bending rolls. The curvature at the bend would not be less than a radius of 20 or 30 feet, and yet the material cracked in two or three places. He believed the cause in that case was the impurity which had accidentally got into the metal, but it would be interesting to know how those impurities affected the bending quality of steel; and the behaviour of ferric sulphides and phosphides should be studied in the same way that the carbides had been studied.

The Manchester Steam Users' Association had recently come across some steel which, although it would weld exceedingly well, cracked after the welding was finished. That was another property of some steels about which one would like to be enlightened. His own belief was that there were many other subjects which might still be worked at experimentally, and seeing what an impetus to researches the formation of the Alloys Research Committee had given, he hoped that it would be re-appointed, even if only for the collection of information which might be offered, or for guiding experimenters.

Dr. T. K. Rose (of the Royal Mint) said he would like, as an old student of Professor Sir William Roberts-Austen, to add his congratulations to the others which had been offered to Professor Gowland and to Mr. Merrett, because he felt sure that anyone who looked through the Report would agree that it was in no way inferior to the other Reports which had been presented and admired so much from time to time. When the Sixth Report was first projected, he was given to understand that one of its results would be a critical and complete analysis of the curves of equilibrium of the carbon-iron series which had been originally put forward in the Fifth Report, and subsequently so fully discussed by Professor Roozeboom. Further experimental proof however was required, and this might have been obtained from some of the experiments described in the Report. For example, if one wanted to determine the constitution of 1·3 per cent. steel at, say 720° C. (1,328° F.) a little above the W point, the natural course to adopt would be to heat it to 720° for twelve hours and then cool it suddenly to the ordinary temperature, where the changes in constitution and structure were necessarily slow; and then carefully examine the specimen to see if austenite, cementite, and graphite were really present there. He thought Professor Gowland had at command a vast amount of information on the subject if he chose to supply it, and therefore probably he could say whether the curve would stand as it was now, or whether there would be alterations in it.

Assuming that the curve would stand as it was now, of what use was it going to be? There was one use which Professor Gowland doubtless realised, and yet he, Dr. Rose, was not certain whether it was clearly expressed. He did not feel sure that, if one looked at the Report for the first time, it would be sufficiently impressed upon one that the portion of the curve on Plate 3 in the left-hand corner relating to the separation of ferrite and cementite was a guide to the right temperature at which steel should be quenched. He would like to ask Professor Gowland in the first place what were the data on which the first paragraph of page 51 was based. It was stated there that Sir William Roberts-Austen believed that a 0·8 per cent. carbon steel could not be hardened very much below 850° C. (1,562° F.). There were no data at the Mint in regard to that, nor any details of the experiment, though they would like to have them very much, because it was a matter of very considerable importance to those who were in charge there. He might recall the fact that Brinell tested a steel containing 0·7 per cent of carbon, 0·3 per cent. of silicon and 0·2 per cent. of manganese, and found that, if quenched, at 690° C. (1,274° F.) it had a hardness in his absolute scale of 241; that if quenched at 750° C. (1,382 F.) it had a hardness of 744—three times as much—and on quenching at 1,000° C. (1,832° F.) it was also 744. Their results at the Mint agreed more or less with that and with other results of Brinell. Steel must of course be quenched at different temperatures according to its composition. One could not expect to harden a steel completely, if one tried to quench a mixture of cementite and martensite, or of ferrite and martensite, even if the steel was quenched above the Ar point, but below the point at which the cementite or ferrite was separated. The mass should be homogeneous at the moment it was quenched, in order to get complete hardening. The result of that was that one could not say definitely that 900° C. (1,652° F.) or any other temperature was the correct one at which steel should be quenched, without giving its composition. In contradistinction to that belief (page 51), they at the Mint found that steel with 0·8 per cent. of carbon would quench very well if quenched at 750° C. (1,382° F.), but that a 1 per cent. carbon steel, containing only 0·1 per cent. of manganese, if quenched at 800° C. (1,472° F.) would not be glass-hard, and would not be suitable for Mint purposes. The curves of equilibrium were undoubtedly of great value, for they showed, with pure steel, at what temperature the steel should be

(Dr. T. K. Rose.)

quenched. He understood Dr. Glazebrook was directing a re-determination of those curves, and when that had been done the results would be of the greatest value to them.

There were other points in his mind, but he would not touch upon them on the present occasion. He would, however, venture to make one appeal to Professor Gowland, who had spent much time and trouble in writing that Report, which was one of extraordinary complexity. There was in the Report an immense amount of detail, and as Professor Gowland must know so much more about the Report than one could possibly glean from reading it through once or twice, he would like to ask if he would be good enough to present a summary of the conclusions which he would himself draw from the Report, if only to save the time of others who might be trying to master it.

The PRESIDENT said the discussion would be adjourned until Friday, 29th inst. There were many speakers, among them Sir William White and Professor Arnold, who had not been able to be present that evening, but who he thought would be at the next.

Discussion on Friday, 29th January 1904.

The CHAIRMAN (Mr. T. Hurry Riches, Vice-President), before proceeding with the ordinary business of the meeting, apologised for his presence in the chair. The President had been unavoidably prevented from attending, as were also the senior Vice-Presidents, and therefore he filled the position as a stop-gap. Before calling upon the members to continue the discussion, he reminded the meeting of the gentlemen who formed the Alloys Research Committee. They were:—Sir William H. White, K.C.B., LL.D., D.Sc., F.R.S., Chairman; Sir Edward H. Carbutt, Bart., Past-President; Professor William Gowland; Mr. Robert A. Hadfield; Professor Alex. B. W. Kennedy, LL.D., F.R.S., Past-President; Mr. John G. Mair-Rumley;

Professor W. Cawthorne Unwin, F.R.S.; and Sir Thomas Wrightson, Bart., M.P. He was sure every member of the Institution would feel he owed a great debt of gratitude to the gentlemen who formed the Committee.

Mr. J. E. **Stead** said he took a very great deal of interest in the Report, firstly because he happened to have studied very considerably the effect of heat upon steel, and secondly, because the particular samples of steel on which the experiments were made were really supplied by him in a roundabout way to the Alloys Research Committee. As a matter of fact, one of his friends in Sheffield very kindly prepared for him a large quantity of pure steel in round bars. Mr. Harbord heard of this and asked him if he could have a certain quantity of the samples for experimental purposes. Those samples eventually got to the Mint, and were experimented upon by the late Sir William Roberts-Austen and his assistants. It might be interesting to the meeting if he narrated the history of the steels, as there was no information given regarding that point in the Report. No. 1 sample given in the Table was basic steel made at the Wigan Coal and Iron Co.'s works in the basic furnace by the Saniter process, and it would be found that it compared remarkably well with the steel of Swedish origin. Its only peculiarity was that it contained a little more arsenic than the other samples. No. 2 sample was Swedish Bessemer. All the rest were melted in crucibles and were made from high-class Swedish material. He might also inform the members that after leaving the rolls they were all cold reeled, that is, they were rolled longitudinally so as to make them perfectly cylindrical and to give them a fine dark polish. Referring to the results of testing the steel, it would appear that the mechanical properties were anything but first class. It was interesting to note that fact because apparently it showed that, although reeling did improve the appearance of bars in the reeled condition, they were not so good mechanically as they would have been, if they had not been reeled at all. Of course Sheffield steels were rarely used in the condition in which they left the reel, but were afterwards reheated and worked up for various purposes, so

(Mr. J. E. Stead.)

that it did not matter very much, from a mechanical point of view, whether they were reeled or not.

He had prepared a diagram, which would perhaps assist those who had not previously studied the effect of heat on the internal structure of iron and steel to grasp what metallographers meant by the terms "solid solution" and "diffusion of carbon." Fig. 163, Plate 40, represented six bars which had previously been made coarsely crystalline by very slowly cooling down in the heart of a ladle of molten blast-furnace slag. All of them were heated at one end to a little above 1,000° C. (1,832° F.), and were comparatively cool at their other extremities. The temperature at equal distances along the bars between the heated and cool ends was determined by means of a Le Chatelier pyrometer. After heating until the temperature remained constant, each bar was quenched in cold water and was ground down on a grindstone, till the whole of the slightly decarburised surface skin was removed. The metal below was then polished and etched.

No. 1 bar, consisted of pure iron. No apparent change in structure occurred until a temperature of 870° C. (1,598° F.) was reached, but at this point the crystalline structure was re-organised and the crystals became fine.

No. 2 bar, contained 0·2 per cent. carbon. In proportion as the temperature exceeded 750° C. (1,382° F.) the carbon diffused from the carbide areas into the surrounding ferrite, until at about 1,000° C. (1,832° F.) diffusion was complete.

No. 3 bar, contained 0·4 per cent. carbon. Diffusion was complete at about 830° C. (1,526° F.).

No. 4 bar, contained 0·6 per cent. carbon. Diffusion was apparently complete at about 770° C. (1,418° F.).

No. 5 bar, represents pure pearlite steel, which contains 0·9 per cent. carbon. Diffusion or "solid solution" of the carbide and iron appeared to be complete at 690° C. (1,274° F.).

No. 6 bar, is typical of steel containing 1·4 per cent. carbon. The white portions represent cementite in excess of the eutectoid proportions.

In the 2, 3 and 4 diagrams the white parts represent the ferrite which is in excess.

The sudden quenching retained the carbon in the position in which it was when heated. The very dark parts indicated the regions where carbon had diffused. The half-tone portions represented pearlite. The junctions between the dark and half tones represented the critical point Ar_1.

He thought that when the members looked at those diagrams they would understand how it was that, on quenching the steels from a high temperature when the carbon was diffused and reheating them again at a low temperature, at a temperature lower than was sufficient to cause the re-formation of the banded form of pearlite, a very homogeneous steel was obtained. Professor Gowland had described such steel as sorbite. He (Mr. Stead) thought the name was, for convenience, a suitable term to use for steels of that kind; it meant possibly what Professor Arnold had described as steel in which the carbide was in an emulsified state.

Referring to Tables 2 and 9 they would find results which were of a somewhat unique character. In Table 2 (page 26) results were given showing that by heating the bars to a temperature of 620° C. (1,148° F.) the elastic limit was very much raised. It was somewhat surprising, also, to find the same thing in Table 9 (page 44), representing steels soaked for a long time at 900° C. (1,652° F.). So important were the observations, that he thought it would be advisable to have them repeated and confirmed.

His own name had been mentioned in connection with the soaking of ingots at 900° C.; and although Professor Gowland never entertained the idea that he (Mr. Stead) had suggested that the bars should be "soaked" at that temperature, the Report might lead to that conclusion. As a matter of fact he had very strenuously opposed any such thing as soaking bars at 900° C. He advocated heating up as rapidly as possible to between 850° C. and 900° C. (1,562° F. and 1,652° F.), varying according as the carbon approached 0·5 or 1·0 per cent., and then to cool in the air as rapidly as possible, and where the mass was great, the cooling should be accelerated by oil or water quenching.

Photographs were given of a cast-steel tool which had been used in America for turning purposes, Figs. 151 to 154, Plate 38. He

(Mr. J. E. Stead.)

remembered an engineer informed him more than thirty years ago that when he had a particularly hard material to turn, which no tool steel would attack or touch, he used white cast-iron, which was ground into shape, and he succeeded with this where ordinary steels of the very best and hardest kinds absolutely failed.

With reference to austenite, it will be remembered that when the previous report of the Committee was discussed it was pointed out, and very rightly too, that austenite (pure carbon steel) had no practical value, but events had since proved that austenite did cut. In his opinion, it was one of the most valuable constituents of rapid cutting steel of modern make. Quite recently he had made a special study of such steels and had found that they contained austenite; or if not austenite something closely resembling it, and he believed that their great toughness and their ability to stand up against the work of the machine was due in part to the presence of that constituent.

He complimented the authors upon the enormous amount of work they had done. There was much of very great interest, and there was a great deal also which was suggestive and would lead to more experiments. He believed that one result of the Report would be to lead other people to follow up similar researches.

Professor J. O. ARNOLD in the first place wished to congratulate his friend Professor Gowland on his accession to the leadership of the British section of the Allotropic Party, and wished that he could extend those congratulations to the Report. In the opinion of many, not all confined to the Carbonist School, those responsible for the issue of the Report had committed a rather grave error of judgment, since its publication inevitably involved criticism. The Report was remarkable for two things, firstly for that which it contained, and secondly for that which it did not contain. The Report might also be divided into two parts, namely the theoretical and the practical. Dealing with the first, or theoretical portion, he had, in the interests of scientific truth to suggest, however reluctantly, that the theoretical views put forward were something in the nature of a cloud of scientific dust raised to obscure the fact that the objects for which the Metallurgical Relief Expedition, organized by the Institution thirteen years ago, set out, had not been achieved. These objects were most clearly and distinctly stated in the first three pages of the First Report.[*] They were to ascertain if the actions of elements on iron were similar to the actions of elements on gold, which it was alleged had been proved to be in accordance with the law of atomic volumes. He submitted that the theory of the law of atomic volumes, as applied to iron, died in the Hall of the Institution of Civil Engineers in May 1894, when he read a Paper on "The Physical Influence of Elements on Iron,"[†] which proved conclusively that their mechanical properties had no connection whatever with the periodic law of Newlands and Mendeléeff. The decisive facts contained in that Paper had never been quoted in the Reports. In the year subsequent to the publication of the Paper, the President of the British Association, a Vice-President of the Institution of Mechanical Engineers, publicly declared in his Presidential Address[‡] that the truth of the law of atomic volumes as applied to iron had been experimentally verified, and that it was now possible to exactly predict the influence of any given element upon steel. The anti-climax to the latter assertion came in 1900, when it was discovered in the laboratories of the University College of Sheffield that vanadium, an element with an atomic volume of 9·3, so far from softening mild steel as it should have done in accordance with the law of atomic volumes, possessed almost magical stiffening powers, so much so that so small a quantity as 0·2 to 0·3 per cent. of the element added to mild structural steels had the capacity of nearly doubling the elastic limit and the maximum stress. The law of atomic volumes with reference to gold died in the University College of Sheffield in the succeeding year, 1895, when his Council, to enable him to decide the point, gave him £500 or £600 worth of gold to experiment with, and its obituary notice was published in "Engineering" on 7th February 1896.

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[*] Proceedings 1891, page 543.

[†] Journal, Iron and Steel Institute, 1894, I, page 107 *et seq.*

[‡] President's Address to the British Association, 1895.

(Prof. J. O. Arnold.)

Turning to some of the theoretical statements made in the Sixth Report, on pages 9 and 10 it was said that the acceptance of the Allotropic theory, and its importance in connection with industrial operations, had justified the work of the Alloys Research Committee. So far as he knew, and he had had unique opportunities of judging in the armour mills, in the gun shops, in the armour-piercing shell factories, and in the cutlery industries of Sheffield, the Allotropic theory had never had the slightest influence. But the Allotropy of 1904 was a shadow of the shade of the Allotropy enunciated in 1891. The Allotropy of 1891 was clearly and distinctly specified to be crystalline polymorphism, and the Allotropy of sulphur was deliberately selected as the type. That view was strenuously and consistently opposed by the Carbonist School, and in July 1901, as the result of a beautiful research, Osmond disproved the existence of any crystalline polymorphism in iron; and as one would expect from a scientist, he unequivocally abandoned in that respect the views he had so long maintained.* He (Professor Arnold) suggested that he had a right to ask Professor Gowland why that all-important declaration of his distinguished leader had been excluded from the Sixth Report.

It was stated (page 9) that Van't Hoff had authoritatively stated that β iron was capable of dissolving carbon to form martensite, and that statement confirmed views persistently advocated in those Reports. It seemed almost incredible, but it was nevertheless true, that the main conclusion drawn from curves published in the Fifth Report was that carbon was practically insoluble in β iron. He submitted that curves which could prove one year that carbon was insoluble in β iron, and two or three years afterwards that it was freely soluble, were capable of proving anything; and the inevitable corollary to the proposition was that curves capable of proving anything necessarily proved nothing. But why should the statement of Professor Van't Hoff be authoritative? He was a great authority on the physics of saline solutions, but his authority on the physics of steel was not generally admitted. The authority which settled the solubility of carbide of iron in β ferrite was an authority much greater than Professor Van't Hoff or any other Professor; it was settled by the unimpeachable decision of experimental fact. In a Paper on the Diffusion of Elements in Iron, issued from the University College of Sheffield in May 1899, and read before the Iron and Steel Institute, it was clearly shown that in iron containing only 0·05 per cent. of carbon, carbide of iron freely diffused or dissolved in the β range of temperature. The Allotropists set up an ingenious theory that in some mysterious way that action was due to the occult influence of the traces of carbon present. In May 1902 a Paper on the Micro-structure of Hardened Steel was issued from the University College of Sheffield, and read before the Iron and Steel Institute, in which it was shown that employing chemically pure iron prepared by Dr. Hicks and Mr. O'Shea, and maintaining it in the β range of temperature for five hours, during that period no less than 3 per cent. of carbide of iron diffused or dissolved. He noticed that throughout the theoretical portions of the Report the solution of *carbon* in iron was exclusively referred to, and pointed out that Professor Stansfield, who made and interpreted the Reports, was distinctly inclined to the view that it was not carbon that diffused but *carbide of iron.*

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* "Metallographist," vol. iv, page 249.

Turning to the practical portion of the Report, he had now to alter the criticisms he had intended making, since Mr. Stead had thrown considerable light on the matter, which he was very glad to hear; but he must say that the utterly abnormal character of the steels, upon which the research should never have been made, could not be in any way due to reeling. He had regularly tested dozens of reeled bars manufactured from low-carbon steel. The influence of reeling certainly could be felt in the mechanical tests, but to a very small extent. The steels mentioned in the Report were absolutely abnormal. In Table 1 (page 24) it would be seen that a steel with 0·47 per cent. of carbon gave an elongation on 2 inches of 6·3 per cent. It was only due to the compilers of the Report to say that they marked it abnormal. Of course it was. But he would ask practical engineers what they thought of a forged steel containing only 0·18 of carbon, giving an elongation of

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only 12·5 and a reduction of area of 29·7. That could not possibly be due to reeling. He was perfectly certain there was something radically wrong in the manufacture of the steels. It was extremely difficult to manufacture nearly pure iron and carbon steels without introducing some oxygen, which considerably modified their properties. He submitted that the question of the mechanical influence of carbon on iron was somewhat ancient history; it was thrashed out before the Institution of Civil Engineers in 1895.* A set of properly made carbon and iron steels were made, and the curves were determined. If anyone would take the trouble to compare the curves figured in that Paper and those published in the present Report, they would see at once that the curves given were really the co-ordinates of stress and carbon. The curves in the Report were so absolutely erratic, that there must be some disturbing influence which altogether destroyed their accuracy.

He also suggested that the labelling of some of the curves should in the interests of the Institution be altered. He noticed a point described as "breaking strain?" What was "breaking strain?" So far as he knew the stress-strain diagram had co-ordinates of tons per square inch and extension. "Breaking stress" would have been better, but even that would be wrong, because it was difficult to determine the breaking stress. He took it that what was meant was the maximum stress, and he thought it would be well to alter it to that.

On Fig. 28, Plate 17, the author suggested that the extraordinary properties of the bars were due to the presence of the alleged constituent sorbite. The sorbite was contained in the scanty dark areas, and it was really evenly divided pearlite, which had no right whatever to a separate classification. He asked the members to ask themselves the question if those isolated patches in any condition whatever could make a 0·13 per cent. carbon steel register a stress of 30 tons with an elongation of only 20 per cent. on 2 inches. The steels were not right, and it was a great pity such an enormous amount of labour had been put upon such unsatisfactory materials. If the Alloys Research Committee had asked him, he would have been exceedingly glad to have given them a complete set of properly made steels of infinitely greater purity than those upon which they had experimented. Another point brought up by Mr. Stead was that he said the cutting properties of high-speed steels were due to the alleged constituent, austenite. Austenite was a constituent essentially formed according to Osmond by very rapidly quenching steel containing over 1·5 per cent. of carbon. In high-speed steels, so far as he knew, the maximum content of carbon was about 0·8, and such steels were never quenched. Mr. Stead's suggestion seemed therefore to fall to the ground.

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* Proceedings, The Institution of Civil Engineers, 1895-6, vol. cxxiii, page 127

There was one final point with which he wished to deal, which was, he thought, of more importance than anything he had yet touched upon, namely, the question of heating brittle steel to about 900° C. (1,652° F.), and allowing it to cool in air to restore it. There seemed to be an impression that that was a new process. He had taken the trouble to try and trace it back to its source, and had found that it was invented in Sheffield in 1820 by one Charles Wardlow, the founder of the celebrated house of Wardlow, which was in Sheffield to-day; only those who were best capable of judging did not call it "restoring" steel, it was rather referred to as "faking" steel.

Through the kindness of his friend Mr. Milton, the Chief Engineer of Lloyd's, he was able to give the Institution some extremely important information on the alleged restoration of steel. The experiments were made, not upon artificially spoiled steel, but one was made on a 1-inch thick boiler-plate, which, under the final hydraulic test, split from end to end like so much glass. The steel on analysis was all right. It was tested mechanically, and the stress was good, the limit was all right, the elongation was all right, and the reduction of area was all right; it was subjected to the most severe bending tests; it was hammered violently over close up, and then bent close up under the machine, without showing a flaw. According to all precedent that was a steel of a splendid quality with faultless chemical analysis and mechanical test, but the fact

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remained that the boiler went like a piece of glass. Fortunately steam had not been into it.

He was commissioned by Mr. Milton, on behalf of the Committee at Lloyd's, to investigate the matter most carefully, more especially with reference to the effect of heat treatment, He had been engaged on the work now for some eighteen months, and, as Mr. Milton had said, the more light that was thrown on the matter, the better he would be able to supplement his verbal report with some remarkable figures which he had sent to Lloyd's. But he wished to say that was only one case of many, some not unconnected with the Navy, in which he had found that once that brittleness—he did not mean brittleness of the ordinary kind, but brittleness under vibration or under alternating stress—was developed in a steel, heat treatment of whatever description aggravated the mischief. That had been conclusively proved, and he, in the most earnest words he could use, asked the Institution of Mechanical Engineers to believe that if once a steel had gone brittle, either mechanically brittle or brittle under alternating stress, the only safe haven for that steel was the scrap heap.

The boiler plates to which he had just referred each weighed about 3 tons. Pieces taken along the fracture line gave the following results: Elastic limit 16 and maximum stress 30·3 tons per square inch. Elongation per cent. on 2 inches 28·5 and reduction of area 51 per cent. Small bending tests $\frac{3}{8}$ of an inch square were violently hammered over a sharp edge to 110°. They were then doubled close up by pressure without showing signs of any flaw. On analysis the plates registered about 0·2 per cent. carbon, 0·5 manganese and 0·05 each of silicon, sulphur and phosphorus. Under the alternating-stress test, described by the speaker at the Congress of the Institution of Civil Engineers in May 1903, the following strictly comparative results were obtained. Satisfactory boiler-plate steel, 1 inch thick, endured in four tests alternations varying from 860 to 916. On heating pieces of this satisfactory plate for half-an-hour at 1,400° C. (2,552° F.) the steel was found to give perfectly satisfactory bending tests, but under alternation endured only 266 reversals. A piece of this spoiled steel was then heated to 900° C. (1,652° F.) and then cooled in air, when it endured only 334 alternations. The fractured boiler plate as received had an endurance varying from 168 to 864 alternations, very strong evidence existed that the bad test-pieces were machined from the inside and the good test-pieces from the outside of the plate.

Through all thermal treatment the pairs containing one good and one bad specimen maintained their relative properties, one enduring only about half the alternations necessary to fracture the other.

For instance, inside and outside test-pieces were heated to 900° C. (1,652° F.) and cooled in air; one endured 500 and the other 260 alternations. Another pair were heated at 950° for half-an-hour and cooled down during about 6 hours. Of these, one endured 782 and the other 388 alternations. A third pair were water-quenched from 950°: one endured 314 and the other 156 alternations. A fourth pair were oil-quenched from 950°: one endured 630 and the other 240 alternations.

In a second experimental series, the severity of the test was diminished till good boiler-plate steel endured about 1,400 alternations. Under these conditions an oil-quenched pair from the bad plate gave the following results: the outside piece fractured after 1,378 reversals, the inside piece endured only 694 alternations. In another boiler having $\frac{15}{16}$ inch thick shell plate, the end plate split right across diametrically under steam. Under the more severe of the two tests just described, this steel, under alternating stress, gave results varying from those of good boiler-plate steel, namely 814 reversals down to only 450 alternations before fracture.

On heating a pair of test-pieces to 900° C. (1,652° F.) and cooling in air, one bar stood 380 and the other 280 alternations, the restorative treatment having made bad test-pieces worse.

These results were only indicative of a large number of tests which he hoped to be allowed to embody in a formal Paper, as it was of the utmost importance to engineers that such facts should be fully discussed, and if possible, explained.

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He had observed with interest Mr. Stead's diagram, Fig. 163, Plate 40, representing the micro-thermal transformations at the so-called critical points of steel, but regretted that his own observations did not agree with those of Mr. Stead, whose diagram, at any rate from the second compartment onwards, involved an initial and cumulative error, which, in the last division representing the transformation of 1·4 per cent. carbon steel, had become colossal. As a matter of fact, such steels presented only a single point of transformation on heating, namely Osmond's (Ac 1–2–3) at about 710° C. (1,310° F.) The diffusion or solution of the cementite was also inaccurately represented. The actual facts on heating and quenching a supersaturated steel containing 1·4 per cent. carbon were represented with substantial accuracy in the diagram,* Fig. 165, Plate 41. At (Ac 1–2–3) about 710° C. the pearlite cells or crystals formed hardenite, having an empirical composition corresponding from a practical point of view with the formula $Fe_{24}C$.

Passing from about 710° (1,310° F.) to 900° C. (1,652° F.) the cementite *segregated*, forming first into thicker cell walls and then into detached masses. About 900° C. the cementite and hardenite inter-penetrated or diffused, and at about 1,000° C. (1,832° F.) were in molecular mixture. On quenching, the cementite again segregated, forming small cell walls enclosing cells of hardenite, much cementite also appearing in fine lines and varying planes, marking lines of cubic crystallization within the little cells of hardenite. These facts he had proved experimentally very many times.

Mr. R. A. HADFIELD heartily congratulated the author upon the way in which he had presented his Report. Everyone knew it was not an easy task to take up the work of a distinguished predecessor, but Professor Gowland had conducted his researches in a very able manner indeed, and therefore he offered him his heartiest congratulations. He also desired to congratulate Mr. Merrett and

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* This diagram does not hold good for "soaked" steels, since with sufficient time cementite segregates below 750° C. (1,382° F.).

Mr. Harbord, the latter of whom had just brought out a new work on the Metallurgy of Steel, for which he was entitled to their heartiest thanks. Few Englishmen had written a work up to the present on that subject; engineers in the past had had to refer very largely to Howe's well-known work, but Mr. Harbord's recent publication was a work thoroughly up to date on a very important subject, to which anyone could refer with the utmost certainty, and know that the facts given were quite correct. He also wished to state that the views of Mr. Harbord, as expressed in his book, with regard to allotropy were very moderate, and it was a great pleasure to find him stating the views he had done on that important question. As a member of the Alloys Research Committee he (Mr. Hadfield) wished to point out that there were in the Report some rather strong statements on the question of allotropy, and he was sure he would not be transgressing if he said that the opinions expressed were not those of the Committee. As a Committee they took no sides whatever and expressed no opinions, and therefore they were presented more or less as those of the late distinguished author or originator of the whole Report, and not those of the members of the Committee itself. He could not help referring to that fact because it was said (page 9): "It is now known that the allotropic changes in the iron itself are the all-important factors." He thought it would have been much better if the word "believed" had been used instead of "known," because as a Carbonist he did not think that up to the present time there were any known facts; all statements were purely theoretical. Mr. Harbord, in the book he had referred to, had shown that the late Sir William Roberts-Austen and Professor Howe did not quite agree in their definition of allotropy. Sir William defined allotropy as "a change of internal energy occurring in an element at a critical temperature, not necessarily accompanied by a change of state." Professor Howe's definition was: "Allotropy is a change in the properties of an element without change of state." Until a clearer statement was forthcoming by supporters of the theory, he did not think they could give their full consent and sanction.

There was a very strong statement (page 10) that the theories held on behalf of carbon alone had had to be abandoned. As a Carbonist

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he did not at all agree with that statement; there was no more proof that a Carbonist need abandon his theory now than there was when the First Report of the Alloys Research Committee was published. Those who had read Mr. Field's remarkable Paper on the Condition of Carbon in Iron—Mr. Field was an American who had been working very hard at the subject—would admit there was a great deal indeed yet to be said on behalf of the carbonist theory. The members knew that the originator and greatest supporter of the allotropic theory was their very respected and able friend M. Osmond, of Paris. They all had the most profound respect for what he said, but M. Osmond did not put the allotropic case as it was presented in the Report. Carbonists did not object to allotropic propositions, but they could not admit that they were proven. Those who were present when Professor Le Chatelier spoke in the Hall only a fortnight ago would remember he said that their knowledge regarding the allotropic transformations of iron and steel had not yet been very much advanced. Professor Le Chatelier was in constant contact with M. Osmond, and he thought a strong statement of that kind was important evidence that Carbonists could not admit all that had been claimed on behalf of the allotropic theory. In saying that, he was objecting chiefly to the statement that there was a β "diamond-hard" form of iron. It was quite possible that iron might change its form, but he thought not in the way that had been hitherto presented. He thought it was time a truce on the question was called, and he suggested that this might be brought about by the Research Committee; he did not quite know how at the moment, but under Sir William White's able guidance he was sure it could be arranged, whereby those who represented the carbonist theory, and those who so strongly represented the allotropic theory should meet together and see if it was not possible to find some common ground upon which to work. He and other Carbonists were only too willing to admit that Sir William Roberts-Austen, M. Osmond, Professor Howe and other allotropists had done magnificent work in the past, and they would be only too delighted if there was some possible way of bringing about a better state of understanding on such an important matter.

With regard to the carbonist theory and the cause of the intense hardness of hardened steel, M. Osmond had recently made an important statement, and he (Mr. Hadfield) thought a concession. While discussing one of his (Mr. Hadfield's) Papers, M. Osmond had recently stated some important facts, and as those facts had not yet been mentioned on this side of the water—they had only, so far as he knew, appeared in a very recent American publication—he would, with the Chairman's permission, refer to them. M. Osmond had admitted that the three principal modifiers of iron were hardening carbon, manganese, and nickel, which he thought went largely to prove the case of the Carbonists. The Carbonists said that hardening carbon had a remarkable influence upon iron, an influence which they did not yet understand. M. Osmond acknowledged that statement when he stated that 1·65 parts of hardening carbon were equal to 11 of manganese and 29 of nickel. He thought that was the very point for which Carbonists had been contending so long. He himself was inclined to go further than that. Everyone knew the extraordinary influence of phosphorus upon iron. The presence of 0·10 per cent. of phosphorus in iron represented bad steel, whereas 0·01 was exceedingly good steel. If it was possible for such minute quantities of phosphorus to produce such extraordinary effects upon iron, was it not possible that carbon had ten times or perhaps a hundred or a thousand times the influence of phosphorus; and, if so, in that alone he thought they found to a large extent a satisfactory explanation as to the phenomena noticed in hardening. His firm had been carrying out at the works for a number of years a most exhaustive series of experiments, for the purpose of ascertaining what were the differences in the percentages of hardening carbon present in steel. It was a most difficult task, to which he wished his friend Mr. Stead could devote part of his time; but Mr. Stead had so many questions under examination that, he regretted to say, the Institution had not for a long time had communications from him on this interesting subject. About 10 or 12 years ago he thought Mr. Stead intended to take up that line of research specially, and he sincerely wished that he would yet find time to do so. It seemed to him that if some method on the chemical

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side could be found of correctly determining the amount of hardening carbon in steel, it would be of the utmost importance. He believed that most minute changes in the quantity of hardening carbon present had the most profound influence upon the character of iron.

Referring again for one moment to the allotropic theory, he wished to propound a question to those who supported that theory. For some months past, in conjunction with Professor Dewar, he had been carrying out some important tests regarding the effects of low temperature upon iron. He was greatly indebted to Professor Dewar for the interest he had shown in the work. He had much pleasure in showing that evening two very remarkable specimens; he was not aware that any public reference had before been made to exactly the same results as he hoped to show the members shortly. He held in his hand a specimen of almost pure Swedish iron which contained 99·89 per cent. of iron, about 0·03 per cent. of carbon, and mere traces of sulphur and phosphorus. Two similar specimens were submitted to Professor Dewar, and one of them, tested at the ordinary atmospheric temperature, gave a tensile strength of about 21 tons per square inch, with an elongation of about 25 per cent. on a length of 2 inches. The second specimen of the same material was submitted to the low temperature of −180° C. (−356° F.), when the tensile strength ran up to, one might safely say, the enormous figure of 54 tons to the square inch with no elongation. What had occurred in that iron? The half of the test-bar of the second specimen submitted to the low temperature after returning to the ordinary temperature bent double cold, and the tensile strength again became normal. He thought that was a most extraordinary result. One specimen indicated that iron at a low temperature showed extraordinary brittleness, and the other end of the same test-bar, when allowed to go back to the ordinary atmospheric temperature was bent double cold, showing that the molecular condition was purely temporary. The same specimen, when submitted to magnetic observation, showed that the magnetic conditions of the sample remained practically the same under the various conditions. The allotropic theory would rather lead to the proposition that β iron was non-magnetic, but the sample he had showed remained magnetic throughout the whole career of its testing, and was brittle; while, on the other hand, the other specimen was in its toughest condition, and he could not himself see how the allotropic theory could supply a proper explanation of that fact. He thought it was due to the form of molecular change, which was entirely outside all chemical action. The same remark applied to manganese steel, which was non-magnetic at ordinary temperatures; it was also non-magnetic at extremely low temperatures. One could not explain the discrepancies by the difference in the form of the iron present, because, apparently, in regard to the magnetic or non-magnetic qualities, they were entirely the same.

In regard to the Report itself, he was very glad indeed to hear Mr. Stead's explanation as to the way in which the steel was manufactured, and he would like to ask him, if possible, for one other piece of information, which, he hoped, he would not have any objection to giving, namely, by whom the steel was made. There had been some confusion in his own mind as to how the specimens were made, whether they were basic steel or crucible steel, but Mr. Stead had explained that point. He thought Mr. Stead said they were made by Messrs. Andrews; if that was so, it was a guarantee of very excellent quality.

With regard to the facts given on page 26, he confessed that he, like others, was very much puzzled in regard to the elastic limit. Specimens were there given showing 0·18 per cent. of carbon and yet an elastic limit of 90 per cent. of the ultimate strength. Those were very remarkable specimens, and he thought it would be best if the experiments could be repeated in some way on a sensitive machine. It might be there was some slight elastic limit that had not yet been noticed, which would be observed at lower tensile stresses. With regard to the saturation point mentioned on page 28, he was very glad indeed to notice that the Report took cognizance of that important point, discovered by Professor Arnold; he wished to give that gentleman full credit for first bringing before the notice of steel-makers that very valuable fact. Few, if any, steel-makers had recognized that the particular point at which saturation occurred was

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between 0·8 and 0·9 per cent. of carbon, until Professor Arnold carried out his historic work some eight or nine years ago. It specially applied to those who dealt with hard steels in making shot and shell, and the indications first set forth by Professor Arnold had been of the greatest practical value, a point at which the Institution specially aimed. He would like to ask the author if he could give any further information on some of the statements made on page 47. It was there stated "Further, it is well known that imperfect quenching sets up internal strains in steel which are not entirely eliminated by the subsequent annealing, owing to the variation in the density of the metal throughout the mass." His own practical experience indicated that if a material was not hardened, there could be very little real strain produced, that is, the stress produced by quick quenching did not strain the metal in any way. Perhaps the author would give some further explanation on that point. He again took the opportunity of thanking Professor Gowland for the great trouble he had taken in preparing such a very important research.

Mr. STEAD, in answer to Mr. Hadfield's question, said he was afraid, after the remarks of Professor Arnold in regard to the steel bars, that were he to give the name of the makers, either Professor Arnold or he himself might be drawn into a libel case. He might inform them that they were steels manufactured in the ordinary way of business, such as were constantly sent out to customers; they were manufactured by a firm of very high standing, and every one of the whole series must be regarded as of excellent quality.

Professor W. CAWTHORNE UNWIN said that as one who belonged to no metallurgical school, he felt a great deal of diffidence in interposing in the present battle royal between two important schools of thought. All he had to say related to quite small matters. He could not help thinking that if there were anomalies in some of the experiments, one reason was they were made on such very small test-bars. The test-bars were only a quarter square-inch area and 2 inches gauge-length, and with bars of that size his own feeling was that small defects or other causes introduced anomalies which were larger than were generally recognised in ordinary commercial testing. It would be very desirable, if possible, if the original intention of the Committee could be carried out, and some of the important points re-tested with test-bars of a larger size. One curious point had arisen in the Report in regard to the exceptional ratio of the yield point (it was called generally in the Report "elastic limit") to the breaking stress, which, in spite of Professor Arnold, had often been called breaking strain, and which, as far as he knew, among engineers was never called "maximum stress." He used the word "maximum stress" to his students, but he had never discovered it in an engineering paper.

He thought there were two very possible reasons for the exceptional results given in the Report, and there was one very simple reason, that it was by no means so easy as people supposed to determine the yield point accurately on small specimens on a gauge length of 2 inches. The determination of the yield point was often made by what was called the drop of the lever, which he thought was at times extremely fallacious. It was sometimes made by observing the first visible stretch of the specimen, and sometimes by the autograph diagram. It was least difficult where an autograph diagram was taken, but there was still some difficulty in quite accurately determining the yield point. The next point was a more important one. Many of the steels were very distinctly hard steels, and there was difficulty in testing short bars of such a kind, in avoiding the introduction of bending stresses in addition to the tensile stress. He tested two or three bars for Professor Gowland in a 10-ton machine, using the most sensitive machine he had, but he was not able to satisfy himself that he succeeded in eliminating bending stresses, although he used spherical seatings with the bars he tested. There was no means of knowing, after the test had been made, that there had not been some bending stress as well as the proper tensile stress. The bars tested had screwed ends, and with screwed ends one could not be quite sure of getting rid of the bending stress; the screw threads seated imperfectly on the nuts. If there was any bending stress present, too low a breaking stress was obtained; and, of course, if some of the breaking stresses on the tests made were lower because there was bending stress, then it would partly explain the high ratio of limit to breaking stress which appeared in some of the results. He did not say that that was the case, but he merely threw it out as a suggestion arising out of his experience of testing.

At the last meeting reference was made to the notched-bar tests, about which one heard a good deal at the present time. He had been making some notched-bar tests, and rightly or wrongly he thought some of the ideas held with regard to them were a little erroneous. Notched-bar tests gave relative results very different from ordinary tensile tests. To take one case, in a notched-bar test a very good homogeneous steel, with large ultimate elongation, only gave about half the work to break it that a piece of common wrought-iron would, which had a much lower breaking stress and a much lower ultimate elongation in tensile testing. It was commonly said that the difference between the notched-bar test and the tensile test was due to the fact that the former was made by impact. He did not think it was generally known that, if one notched a bar and broke it in the ordinary way in the tensile testing machine, results were obtained which were not quite so marked, but still wholly of the same kind as if one notched a bar and broke it by impact, and therefore the results which were obtained of notched-bar tests were not specially due to the fact that the bar was broken by impact, but to the fact that the bar had been notched. Notching the bar prevented any elongation or contraction of area in the plane of the fracture. What happened in the notched-bar test was that there was a progressive tear, which probably picked out easy lines of fracture amongst the molecules of which the steel was made up. It had been known for a very long time that, when a bar was subjected to repeated stresses, it broke with sometimes half or less than half its statical breaking load—with a breaking load sometimes even below its initial elastic limit. He had broken a great many bars by such fatigue tests, and where they broke very nicely it was perfectly easy to trace that the fracture began by the formation of a circular fissure all round the bar, which progressed gradually till the bar was so reduced in strength that it broke suddenly. That was a fracture exactly analogous to the notched-bar fracture; and the result obtained in a fatigue test threw some light also on the case of the notched-bar fracture. He had no doubt that notched-bar tests were going to be of considerable value; he had not made up his mind finally about them yet, but there was no doubt they required standardizing, and a little clearer interpretation of them was wanted than was possessed at the present time.

Dr. H. C. H. CARPENTER said the first point to which he wished to refer was the fact that the bars were annealed at 620° C. (1,148° F.). It was quite true, as the author pointed out, that that temperature was below the lowest about which accurate and definite information was possessed, that is, the pearlite point. Nevertheless it was well to remember that in the Fifth Report * of the Alloys Research Committee reference was made in the case of two irons to a point in the neighbourhood of 600° C. (1,112° F.)—that point was obtained with electrolytic iron containing no carbon at all—and also to a steel containing, as far as he remembered, 0·51 per cent. of carbon. It was not obtained with three steels of intermediate composition. He would like to ask Professor Gowland whether cooling curves were taken of the steels, and whether that particular point, which was quite a long-drawn-out one, he believed, was observed in the case of any of them. That might throw some light upon the fact that a difference in the mechanical properties was obtained by annealing at that temperature. The author stated (page 38) that as the mechanical properties of the bars annealed at 900° C. and 1,100° C. (1,652° F. and 2,012° F.) were similar, one might expect that the structures would be similar also, and they pointed out that that was borne out in the case of steels containing up to 0·72 per cent. of carbon, but that the structures were different in the case of the bars containing more carbon; and they concluded from the photo-micrographs that a decomposition of the cementite into iron and amorphous carbon had taken place. He thought they might conclude, from the paragraph which followed, that the author

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* Proceedings, 1899, page 35.

(Dr. H. C. H. Carpenter.)

did not find actually any evidence of the presence of carbon in the sections, because he relied for his proof of that decomposition upon an experiment in which iron carbide was heated up to about 1,200° C. (2,192° F.), and in that case he found that carbon was undoubtedly present. He did not think that case could be accepted as analogous, and he proposed to view the two cases in the light of Professor Bakhuis-Roozeboom's modified diagram of Plate 3. According to that diagram, iron carbide, when a temperature of 1,000° C. (1,832° F.) was reached, would decompose into austenite —he would assume it was austenite for the time—and graphite. That would be one of the points which the authors observed, no doubt; while at 1,130° C. (2,066° F.) the mixture melted, giving a liquid iron-carbon alloy containing 4·3 per cent. of carbon and the rest graphite. This was doubtless the other point observed by the author on his curves. The author was no doubt aware that that experiment had also been performed by Mylius, who showed not only that that decomposition took place, but that the residue consisted of an iron-carbon alloy, containing 4·3 per cent. of carbon, the remainder being graphite. Therefore the decomposition which the author had observed merely confirmed the experiment which was done by Mylius. But it was quite different in the case of the three alloys examined in the Report. Reference to the diagram would show that to take the alloy highest in carbon, that containing 1·3 per cent., at a temperature certainly under 1,000° C. (1,832° F.) in the neighbourhood of 950° C. (1,742° F.), one no longer had iron carbide there as such, but austenite, or martensite, if one so cared to call it, at any rate, iron in the hardened state. There was no reason for supposing that this system was unstable at 1,100° C. (2,012° F.). The same reasoning would apply *a fortiori* to the alloys containing 0·8 and 0·9 per cent. carbon. That being so, he thought it was simplest to assume that the decomposition to which the author referred, into iron and carbon, had not really taken place. He referred particularly to Fig. 81, Plate 23; that was the only one which seemed to him to show a marked difference from the alloy heated to 900° C. (1,652° F.); that contained very definite evidence that what had happened had been that the pearlite had segregated into massive ferrite, on the one hand, and massive cementite on the other. This was possibly connected with a variation in the rate of cooling of the furnace, which the author had admitted was dependent on the temperature to which it had been initially heated. That, he took it, was what the diagram showed. He suggested that to Professor Gowland as an alternative explanation of the photo-micrographs.

He would like also, while on the question of the diagrams, to ask whether there was any good reason for omitting a line which appeared in the Fifth Report (Plate 4, 1899). It was quite true it was a hypothetical line; nevertheless it seemed to him to be necessary—to indicate why it was that, when cast-iron was quickly cooled, graphite was not formed but white iron. Professor Roozeboom suggested that it might be explained by supposing that at the temperature of 1,130° C. (2,066° F.) one did not get the separation into graphite and austenite, but a separation into cementite and austenite at a somewhat lower temperature; and as by theory they were cooling very quickly, as soon as they got to 1,000° C. (1,832° F.) they were in a region where the cementite and austenite formed a stable system. He would like to ask whether that line had been omitted for any good reason, or whether it was merely an oversight. In conclusion, he wished to say that metallographists were extremely indebted to Mr. Merrett for the most valuable collection of photo-micrographs he had given, which would be very useful as a reference.

Sir WILLIAM H. WHITE, K.C.B., Past-President, said it was about six years ago, on the death of the late Sir William Anderson, whose influence had so much to do with the starting of the Alloys Research, that he undertook to succeed him in the post of Chairman of the Alloys Research Committee. He had nothing to do with the previous work, except to read the Reports, and he could not claim to have had any very great personal influence upon the work that had been done since, although naturally he had throughout taken a great interest in the inquiry. He had followed closely the discussions that had taken place, and on previous occasions had the privilege of hearing the battles royal which occurred between Sir William Roberts-Austen and Professor Arnold, in which each maintained his

(Sir William H. White, K.C.B.)

views, and, so far as he was able to judge, neither convinced the other. He thought he understood a little of the merits of the case, but did not propose to give any opinion. He was very thankful there was no reason that the practical engineers, who had to use the materials, need be called in as a jury to decide that knotty question. He thought, if he might say so, that on what was called the "scientific" side (which seemed to him in that particular instance not yet to have reached the stage of real science) matters were left somewhat in the condition of speculation; whereas users of material, and steel makers, had a conviction that the Alloys Research had been one of very great practical value to them and had helped to clear up many doubtful points. He understood Mr. Hadfield to endorse that view heartily. Whatever might be said about the theory of the phenomena governing the structure and properties of alloys, the ascertainment and collation of facts had been of great value to the makers as well as the users of steel.

He thought it was important that they should not, while giving proper attention to the theory of the subject, overlook its intense practical importance. The profession owed a great debt to Professor Arnold for his very interesting and most able inquiries into all that concerned the properties of steel, and if he might say so, he could not help thinking that Professor Arnold, in common with many others, had received fresh incentive from the work done in this Research, and from the difference of opinion that he had entertained in connection with the inquiry. That really was the true scientific view of the matter—they were endeavouring to find out the truth, and the man, who for years was the devoted servant of the Institution in the conduct of the inquiry, was as much a seeker after truth as anybody.

He desired to say one word more about the composition of the Committee in relation to the inquiry. It hardly needed saying, but, as Professor Arnold with great propriety did not treat it as a personal matter, and referred to the Alloys Research Committee and its Report, it was no revelation to state that the Report, and all the preceding Reports, contained simply the work of Sir William Roberts-Austen and his staff. The Research Committee in no sense controlled or joined in the expression of the opinion therein contained. The principal inquirer drafted his own report, and the Committee allowed that to be presented as his Report, as it was quite right and proper they should. But they took no responsibility for the opinions of Sir William Roberts-Austen, based upon his work; and the Committee, acting as the representatives of the Institution, simply made suggestions as to the direction in which they thought inquiries might usefully proceed, and (so far as they could) assisted in any matters of difficulty or policy which were referred to them for opinion. He took it he did not go wrong in saying (and he could say it perhaps better than Professor Gowland), that, as stated in his prefatory note, Professor Gowland had, in the present instance, not attempted any verification or support or endorsement of the conclusions of his illustrious predecessor, but had acted as the most faithful and most obliging servant of the Institution in putting into its final shape the conclusions at which Sir William Roberts-Austen had arrived. It might be that Professor Gowland supported the view which Sir William Roberts-Austen enunciated or adhered to. Whether he did, or did not, did not touch the essential fact that, in the present inquiry, he had simply endeavoured to arrange and to produce for the convenience of the Institution and of the engineering world, a Report for which his famous predecessor had prepared the materials.

The Institution now came to the end of the work which was begun in April 1890. Nearly fourteen years had passed since the beginning of the work, and although it might be said to have practically concluded with the death of Sir William Roberts-Austen, that was a very long period for such an inquiry to have gone on. He thought the Members of the Institution might congratulate themselves that the research had been carried through in the way it had. It had involved a very large expenditure of money, approaching £2,000; there had never been any stint in meeting all that had been asked for. The statement of expenses of course excluded altogether any consideration of the great value of the services of Sir William Roberts-Austen and some of his staff; that was freely given, and the Institution owed those gentlemen a great debt. It would be a misfortune if it should appear that so long and continuous and comparatively costly an effort had failed to produce practical results. He was quite confident that Professor Arnold did not doubt the fact that the money expended had produced results with which they might be satisfied, although Professor Arnold might not agree with the explanations which had been given of the facts, or with the theories which had been constructed to explain experimental results. At all events he could say, as one who had to watch the manufacture of steel for structural purposes, and in connection with the making of armour, for many years, that in his judgment the Reports had been of great practical value. He thought he was not going beyond the truth in saying that some manufacturers—he regretted to say not English—had availed themselves of suggestions contained in the Reports, and turned them to practical account, embodying their work in patents based upon this Research, and so securing the payment of large royalties by English makers for processes the origin of which were to be found in the Reports of the Committee, which he regretted to say had not found as much practical application in England as they should have done, or at as early a date as he hoped might have been the case. It was another illustration of what had repeatedly happened—that English ideas had been put into practical shape and made of commercial advantage outside this country instead of inside it.

It had been said that the Researches of the Committee should have been conducted on a larger scale; he saw a notice a few days ago which suggested that that was the case; that in the series of experiments which had been made larger samples and duplicate tests should have been included. Everyone agreed that that would have been desirable, but he ventured to say that the Institution had done its best in the inquiry, and that the extension of the inquiry might perfectly reasonably be expected to be made by those who were actively concerned with manufacture, who had all the opportunities, and who could now have the skilled assistance of scientific men to carry out the inquiry in their own works. He did not think it was a wholesome thing to suppose that all Research should be conducted in laboratories separate from works. He had the greatest respect for the work done by inquirers like Professor Arnold, or Mr. Stead, in private laboratories, but he hoped to see the time when the example of Mr. Hadfield would be much more widely followed in this country, and when inquiries, both scientific and practical, would be carried out on a very large scale in the works of the manufacturers all over the country. When that came to be done, as he was sure it must be done—it was already being done elsewhere—then he ventured to say that the methods of investigation which had been used in the long series of Reports of the Alloys Research Committee would be found of great value in guiding the inquirers. It seemed to him that the most valuable practical suggestions which had come out of the researches were the following—to mention them seemed now almost like stating truisms, but they must not forget that when the Report began they were not accepted as truisms:—(1) traces of elements profoundly affected the properties of masses of metals, and of steel in particular; (2) that heat treatment greatly affected the structure at critical temperatures; and (3) that the influence of such heat treatment might very well be expected to take the place of much mechanical work. That might be an imperfect summary of the situation, but he thought it meant a great deal. He knew it had been the dream of many steel makers in this country for years that a great deal of mechanical work might be dispensed with, chemical processes and heat treatment being substituted. It was getting on for twenty years since one English steel-maker had the courage to produce a cast-steel armour-plate, which had no work done upon it, and when it was fired at the result was not bad, although, of course, it was not equal to results obtained by other processes. It was also well known that the same firm about the same time made marine shafts on which there was no mechanical work, and made them successfully. What was thus done on a small scale he could not help thinking would be done eventually on a much larger scale, and then, although the inquiries which had been made by the Committee might not be perfect or complete, and although the interpretation of the facts might be questioned, these Reports would be found of immense value as works of reference.

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He was greatly struck by a remark made by Mr. Stead, which exactly expressed one benefit which had resulted from the work of the Research Committee, namely, it had set so many able men thinking and experimenting and finding their own way, thus adding to the common stock of knowledge. When one thought of the work that had been done during the period the Research had been in progress by Professor Arnold, by Mr. Stead, by Mr. Hadfield, and by Mr. Andrews, the benefit which had accrued was self-evident. The apparatus had been immensely improved. The earlier Reports were limited to pyrometric observations, which were very imperfect. He remembered Professor Arnold insisting, at a very early period, upon photo-micrographs being brought in for examination of structure. In later Reports, mechanical tests went on side by side with other examinations of material and the minute study of the structural steel. Work done under the direction of the Research Committee had taken a leading place in the progress, improvement and perfection of knowledge, influencing and stimulating work done in other countries. That indirect result appeared to him to be of immense value as well as redounding to the credit of the country.

Last of all, he wished to say that he hoped and believed, although the inquiry under the immediate direction of the Committee of the Institution might be said now to have approached a close, yet the work would go on. At the last meeting the members heard Dr. Glazebrook state that he was quite willing to undertake the work, and it had been arranged that the inquiry should proceed at the National Physical Laboratory, for which purpose the Council of the Institution had approved of as much of the apparatus as could be used being handed over to the National Physical Laboratory. He trusted that the work would go on in connection with the Institution, although not under its actual direction, and that at subsequent meetings further reports of results might be brought forward, when they might have the benefit of Professor Arnold's assistance and very hearty and thorough criticism, which he was sure they all valued. Professor Arnold had the courage of his opinions, and the members all respected him for that fact, and he trusted that Professor Arnold's work, as well as that of others, would find a permanent record in the Proceedings of the Institution. Captain Sankey, of Messrs. Willans and Robinson, had been good enough to say that he would undertake to make impact tests on the samples described in the last Report, and those results would be added to the Proceedings (page 160), so that one important feature, which was lacking in the original Report, would be supplied by Captain Sankey's kindness.

Mr. J. H. **BELCHER** thought that the impact method of testing, which had been referred to by Professor Unwin and Sir William White, gave rise to rather uncertain results. It might be of interest to the members to know that he had certain tests made by a gentleman, who was an acknowledged expert in the method in question, with the following results:—

(*a*) Pieces of crank-shaft steel gave the comparative number 26 and 37, a difference of nearly 30 per cent., whereas identical results were expected.

(*b*) Two pieces from the *same* bar which had been case-hardened worked out as 14·8 and 19·8 respectively.

(*c*) Three tests on practically *identical* specimens gave the numbers, 1, 0·4, and 1·9.

(*d*) Another set of three from the *same* bar gave as test numbers, 3·9, 8·6 and 6·7.

The method of impact testing where notched-bars were used, as pointed out by Professor Unwin, he believed was only in its infancy, and hence should not be criticised too harshly; all the same it should not be used even as a relative method of determining the good or bad qualities of steels, etc., and, in his opinion, the time had not arrived when it could be depended on for commercial purposes. Much less was that the case in research work, where scientific accuracy was the chief object.

In reference to the quarrel between the so-called Allotropists and Carbonists, the allotropic theory was one which appealed fully to scientific men, and had most certainly given an incentive to much valuable research. Although he was not an Allotropist himself, he honestly said he was unable to follow the *rationale* of some statements made, not only in connection with the last research, but also in the works of men like the late Sir William Roberts-Austen, Mr. Howe, etc. He did not think very much was known about α-, β-, and γ-iron, but at the same time what definite knowledge was there of atoms and molecules which were the foundations of modern chemistry. He maintained however that Osmond's allotropic theory had served a useful purpose by encouraging original research, and for that reason he trusted that the strictures of Professor Arnold would not be looked upon as being in any way final. Although Professor Arnold was quite prepared, he had no doubt, to hold his own as a Carbonist, there was ample evidence that the gentlemen on the other side were also capable of dealing some heavy and sturdy blows.

He would like to mention a small matter of practical importance. In the polishing of steels, mentioned in the Report, the separation of aluminium oxide had been referred to (page 19). It was really a cruelty to ask any busy man to undertake such a course of differential precipitation, when he believed equally good results in the final polish of steels could be obtained by the aid of diamontine used on a piece of ordinary flat polished glass. He had been accustomed to finish up his sections in that manner, and with admirable results. The details of refined polishing he had learnt from watch-makers (he came from a watch-making centre), and trusted that these hints might be of some small practical value. He was obliged to the Institution for giving him a hearing, and, with many others, owed a debt of gratitude to the Alloys Research Committee for their valuable Reports, which, speaking for himself, had encouraged him to do a little private research in this fascinating and highly important subject.

Mr. S. N. BRAYSHAW said that, in the explanation of the phenomena connected with the hardening of steel, he did not belong to any particular school, but he had been exceedingly interested in the work of the Committee. This Sixth Report was full of interest and of direct practical importance. Previous Reports had been of great value to him, because his trade involved the hardening of tool steel.

Mr. Stead spoke about the sharply defined line on the diagram at which steel hardened. He (Mr. Brayshaw), in his work, used resistance pyrometers, and was in a position to say that at the hardening point, 1° C. made a perceptible difference in the hardened steel. Recent work showed that the hardening should be far more accurate than was considered necessary a few years ago. Five degrees Centigrade made the difference between good and bad hardening. He was very much indebted to the Institution for the work it was carrying on.

Mr. F. W. **Harbord** wished to say, in regard to the steels upon which experiments were made, that he had heard Mr. Stead was having a quantity of steel made, and he then asked Mr. Stead if he could get some for him. That was before any question of supplying them for the purposes of the Research Committee arose. The steels were made at one of the leading works in Sheffield; they were commercial steels of the purest quality which could be obtained. Some months afterwards, when Sir William Roberts-Austen consulted him about the research, and told him that he wanted a complete set of steels at once, he (Mr. Harbord) offered those he had ready, in order that the research might be commenced at once. He might further say that the experiments would never have been commenced on the small bars, if it had been anticipated that they would have ended with the small bars. The original intention was to confirm the preliminary experiments by a similar series on large bars. If he had had a special lot of steels made, he was afraid Professor Arnold would have said they were working with fancy steels; they specially selected pure commercial steels, the purest that could be obtained. As he had said, they were originally obtained for another purpose, but he thought they were suitable for the purpose of the experiments.

With reference to the elongation in Table 1 (page 24), referred to by Professor Arnold (page 113), in which the very abnormal results were given, his own suggestion had been that the steels should not be tested as rolled at all. He knew that small bars of that kind must be subjected to all sorts of strain and stress, and he suggested

(Mr. F. W. Harbord.)

TABLE 30.

(Duplicate tests for Table 2, page 26.)

PROFESSOR UNWIN'S RESULTS. As these bars were small in diameter, they were tested in a 10-ton machine. The ends were screwed and carried on nuts with spherical seat. The yield point was determined by noting the first visible stretch.						COOPERS HILL RESULTS. Yield point determined by noting first visible stretch and also by automatic diagram.					COOPERS HILL RESULTS. Given in Report.				
Carbon. Per cent.	Area in sq. ins.	Yield Stress. Tons per sq. inch.	Breaking Strain. Tons per sq. inch.	Elongation on 2 ins. Per cent.	Ratio of yield to breaking strain.	Carbon. Per cent.	Yield stress. Tons per sq. inch.	Breaking strain. Tons per sq. inch.	Elongation on 2 ins. Per cent.	Ratio of yield to breaking strain.	Carbon. Per cent.	Yield stress. Tons per sq. in.	Breaking strain. Tons per sq. in.	Elongation on 2 ins. per cent.	Ratio of yield to breaking strain.
Heated to 680° C.						Heated to 680° C.									
0·180	0·1113	19·23	28·20	26·5	0·68	0·180	16·36	28·72	27·4	0·60	—	—	—	—	—
0·254	0·1092	24·84	32·43	23·0	0·77	0·254	24·01	33·18	27·3	0·72	—	—	—	—	—
0·468	0·1104	27·29	34·97	26·0	0·78	0·468	28·5	35·81	24·3	0·79	—	—	—	—	—
Heated to 620° C.						Heated to 620° C.					Heated at 620° C.				
0·180	0·1021	26·92	33·24	21·0	0·81*	0·180	25·09	31·37	26·00	0·79	0·180	26·50	30·60	33·0	0·86
0·180	0·1032	25·95	31·77	30·5	0·81	—	—	—	—	—	—	—	—	—	—
0·254	0·0999	25·38	32·79	25·0	0·77	—	—	—	—	—	0·254	27·78	34·50	24·0	0·80
0·947	0·1009	35·47	56·66	12·7	0·63	—	—	—	—	—	0·947	34·20	52·90	15·0	0·64
0·947	0·1004	35·44	52·07	—	0·68†	—	—	—	—	—	—	—	—	—	—

* Yield point not very marked.

† Broke close to gauge point.

that they should be heated just below the point at which any carbon change would take place, namely, about 620° C. (1,148° F.) to remove stress due to rolling and cooling, and be called normalised bars. The results in Table 1 (page 24) were obtained not by himself at Coopers Hill, but elsewhere. For himself he should have compared all the results with Table 2. Originally it was arranged to confirm the results in Table 2 by another set of tests, but owing to the letter being mislaid after Sir William Roberts-Austen's death, it was not done. When he saw the Table in print, he managed to find a few bars, some of which were sent to Professor Unwin. The others were tested as duplicates at Coopers Hill. (*See* Table 30, page 138.) The bars were ½-inch instead of ⅝-inch, and were thus smaller than those originally used, but Professor Unwin's results agreed within very reasonable limits with those in the Report and with duplicate tests at Coopers Hill, so that, making all allowances for the error due to the smallness of the bar, he thought there could be no doubt that the results of elastic limit in Table 2 were practically accurate.

Discussion on Friday, 19*th February* 1904.

The PRESIDENT said that unfortunately Professor Gowland was laid up with influenza, and could not be present at the Meeting; but he had been kind enough to prepare very carefully his reply in writing to the discussion which had taken place at the two previous meetings, and the Secretary would read it after any further remarks had been made.

Mr. WILLIAM H. MERRETT said that Professor Le Chatelier in his most interesting remarks (page 96) referred to a structure which was described in the Report (page 54) as martensite. This structure was produced by heating a steel containing 0·4 per cent. of carbon to 720° C. (1,328° F.), retaining it at this temperature for some time, and then quenching it in water. On reference to Figs. 139, 140,

(Mr. William H. Merrett.)

and 141, Plate 36, it would be seen that Figs. 139 and 140 were made up of two constituents, one of which had been actively attacked by the etching liquid, while the other had been hardly attacked at all. Professor Le Chatelier stated that the temperature of quenching was below the point of transformation, and consequently martensite could not have been produced. He further pointed out, as evidence of the absence of martensite, that the metal remained malleable after quenching. It was often erroneously supposed that martensite and ferrite could not exist side by side in the same specimen. On reference to the equilibrium curve for carburised iron on Plate 3, it would be seen that by heating the 0·4 per cent. carbon steel to 720° C. (1,328° F.) at first the pearlite laminae mutually dissolved in one another at 680° C. (1,256° F.), while at 720° C. a small portion of the ferrite also went into solid solution. On vigorously quenching this steel at the latter temperature, one would expect, from the equilibrium curve, to find two constituents, and Figs. 139 and 140 showed that this was actually the case. If the abstraction of heat had been sudden, martensite would probably be present, if not so sudden then sorbite or troosite would be formed. Martensite was recognised by its typical structure of interlacing acicular crystallites, and sorbite was revealed under the microscope as a more or less granular structure. The steel in question was very carefully attacked by liquorice juice, and the photo-micrograph obtained was reproduced in Fig. 141, Plate 36. It would be seen that the typical needle-like structure of martensite had been obtained in the present case.

Many other instances of the occurrence of ferrite and martensite side by side in the same steel had been revealed under the microscope, notably in the case of a rail which fractured with disastrous results at St. Neot's on the Great Northern Railway. On Figs. 105, 106, Plate 22, Proceedings 1899 (page 77) would be seen respectively a structure of the St. Neot's rail and one of a rail which had been submitted to the action of an electric arc. In the former case the rail has been locally heated, probably by the "skidding" of a wheel; while in the latter instance a perfectly sound rail was also locally heated, by allowing the flame of an electric arc to play on its surface for some time. In both cases the surfaces of the rails had been heated considerably above their A_1 points, and the heat had been rapidly conducted away by the main mass of the rail. It would be seen that these rail structures were similar to those given in Figs. 139 and 140. A careful examination of the St. Neot's and the "arced" rails under the higher magnifications of the microscope had in both cases shown the presence of martensite, Plate 42.

Objections had been raised to some of the conclusions of the Report being based entirely on the mechanical tests done for the Committee, namely, the breaking strain, the elastic limit, elongation and reduction of area. It had been suggested that other tests, such as notched-bar and torsion tests, should have been made. These tests would, doubtless, have been very useful, but it was, unfortunately, not possible to carry them out. The notched-bar tests certainly would have been done, had Sir William Roberts-Austen lived. The conclusions were therefore based on the existing specifications for steel, which, in no case, provided for these special tests.

Dr. Carpenter objected (page 127) to the statement on page 38 of the Report to the effect that when the three high-carbon steels (0·871, 0·947 and 1·306 per cent. of carbon respectively) were annealed at 1,100° C. (2,012° F.) for half-an-hour, the resulting loss of strength was due to the decomposition of the iron carbide into amorphous carbon and iron. He would like to point out that they had repeatedly found free carbon in high-carbon steels which had been annealed a little over 1,000° C. (1,832° F.). The fact that iron carbide decomposed at about 1,000° C. into iron and amorphous carbon was indeed made use of in the ordinary production of malleable iron castings by cementation. In an Appendix (page 203) to this Report, by Mr. C. O. Bannister, a number of photo-micrographs were given showing the various stages of the process. Although all the photo-micrographs were from iron containing about 3·5 per cent of total carbon, yet the amount of combined carbon varied from this amount to less than 0·05 per cent., according to the amount of heat treatment the metal had received.

(Mr. William H. Merrett.)

Dr. Carpenter also wished to know whether there was any particular reason for omitting the hypothetical line which appeared in the Fifth Report,* indicating that when cast-iron was quickly cooled graphite was not formed, but the result was white iron. It was well known that it was almost impossible to produce a white iron by quickly cooling a metal containing more than 4 per cent. of carbon. The line was therefore omitted, as it was thought improbable that it indicated the changes which actually took place when a high-carbon cast-iron was cooled.

Mr. Belcher (page 136) advocated the use of crushed bort or diamontine for polishing steels. From his own experience, however, the speaker found that these substances were quite unsuited for the preparation of steel specimens, especially when it was necessary to examine them under the higher powers of the microscope. Mr. Belcher thought that the method described in the Report for preparing specimens was refined cruelty; it would however be found that, by arranging matters systematically, the method was not so laborious as it appeared. The experimenters had used diamontine many times; they had washed it as thoroughly as possible, but in no case could a good polishing be obtained for a high-carbon steel. Diamontine would do perfectly well for brass, but for steel it was absolutely useless.

Mr. Brayshaw stated (page 137) that, from practical experience, he found that 1° C. made quite an appreciable difference to the quenching of a steel, and that a variation of 3° C. was quite sufficient to absolutely spoil it. Mr. Brayshaw did not state the class of steel to which he referred. It was improbable that such small differences would alter the properties of an ordinary carbon-steel, except in extreme cases. The metal referred to was doubtless some type of "special" steel.

Professor **Gowland** wished first to thank the Members of the Institution and all who had been present at the meetings for the very favourable reception of the Sixth Report to the Alloys Research

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* Proceedings 1899, Plate 4.

Committee. The points which had been dealt with in the discussion were, for the most part, of minor importance, or related not to the work which had been done, but to the ground which had not been covered.

As regards the work itself, he might say that it was never intended by the late Sir William Roberts-Austen that it should be in any way exhaustive, but that it should be merely preparatory to an extended investigation on the Heat Treatment of Steel, to be carried out on bars of large commercial sections. It was for this reason that small bars were chosen, and the experiments made with them were conducted solely with a view to the determination of the lines on which the investigation on large bars could be best carried out and useless work be avoided. All who had had to undertake researches on bars of large sections must know well how important it was that time and money should not be wasted on useless experiments, and must, he thought, admit that the course pursued was the right one. Unfortunately, death removed the chief worker before this preliminary investigation was quite completed, and the main research was not even begun.

In this preliminary investigation, however, so much work that was new, so much that was suggestive, was embodied that it was deemed advisable that it should not be lost, but should be presented to the members as the Sixth Report, so that other workers might not repeat the experiments which led to negative results, but might follow up further those which seemed to lead in the direction of usefulness. That the Alloys Research Committee were right in their decision would, he was sure, be admitted by all.

M. Le Chatelier, whose name was so familiar to all as a distinguished investigator of the many problems which surrounded the study of the physical properties of iron and steel, pointed out the importance of supplementing tensile tests by impact tests on notched-bars. He believed this method of testing was to have been adopted by Sir William when dealing with bars of larger sections, and that tensile tests only were made in this preliminary investigation, as they were those in most common use in industrial works and specifications. Captain Sankey had very kindly offered

(Professor Gowland.)

to make these notched tests of all the bars dealt with in the Report, and a large number of bars had been sent to him for the purpose; but, unfortunately, some had not yet been found. There were, however, no bars which had not been subjected to stress, so that the results would not be the same as those which would be obtained from bars which had not been strained.

He had to thank Mr. Harbord for the evidence he had adduced in support of the results of the experimental work (page 138). As regards the heating at 900° C. (1,652° F.) and 1,000° C. and the differences showed as compared with Mr. Campion's work, he agreed with Mr. Harbord they were probably due to the great differences in the sections operated on. He thought that Mr. Stromeyer's objection to the want of torsion tests (page 102) was met by what he had already said about tests of notched-bars.

He was not aware, as stated by Dr. Rose (page 104), that this Report was intended to contain a critical and complete analysis of the equilibrium curves of carburized iron. It was not mentioned in Sir William's introduction, nor in his scheme of the work, hence it had not been dealt with. He agreed with Dr. Rose that such an analysis was very much needed, as several of the experiments in the Report would seem to show that some of the changes in the constitution of carburized iron did not completely take place, exactly at the points indicated by the curves, although not very far from them. The matter known was a very lengthy one, and would form the subject of a Paper by itself.

As regards the hardening of steel for Mint dies, and the statement made by Sir William Roberts-Austen that 8 per cent. carbon-steel could not be effectively hardened in water by quenching much below a temperature of 850° C. (1,562° F.), he might say that Sir William would not have said so, unless he had very good grounds for that opinion, so far as the steel was specified and the method of quenching practice were concerned, the latter being of paramount importance. So far as his own experience went in the preparation of Mint dies, it was impossible to determine the hardness of a steel die after quenching; one might test the hardness of the exterior of the die, but that told one nothing about the interior. One might, however, get a surface of maximum hardness by quenching at 750° C. (1,382° F.), but what about the interior? The only proof one could have that the steel had been hardened sufficiently for the temper required was in the number of coins the die would strike, before showing signs of cracking.

At the Imperial Japanese Mint it seemed that a higher temperature was needed than 750° C., in order that the interior, which was necessarily cooled more slowly than the exterior, should be properly hardened, otherwise, on tempering, the middle portion of the die would sink during work. A Mint die was, however, not very suitable for experiments on hardening and tempering, as the success of these operations could only be measured in its case by the number of coins it would strike before cracking, and this was largely dependent on other causes, notably on the character of the punch by which the die was made. As long as the surface of the punch was nearly a true plane, the dies would strike their maximum number of coins; if it were curved, they would then strike a less number, and when the curvature reached a certain amount they would strike practically none, but would develop cracks at once, however perfectly they might have been hardened and tempered.

He wished to thank Mr. Stead (page 107) for the information he had kindly given respecting the steel used in the experiments, and of which there were no records in the late Sir William's papers. He was also much indebted to him for his very valuable contribution to the discussion, on the changes that occurred in heating steels possessing a very coarse structure, when the temperature ranged from a low to a high degree. He was sorry that the paragraph in which Mr. Stead's name was mentioned was liable to misinterpretation; it should have read "reheating low-carbon steels," instead of "annealing certain classes of steel."

The first part of Professor Arnold's criticism might almost be termed a complaint (page 110). It had no relation whatever to the Report, but concerned only the previous Reports which had been issued by the Alloys Research Committee. These had already been fully discussed, and required no defence from him.

(Professor Gowland.)

As regards the allotropic theory, with which Professor Arnold was not in agreement, he might say that its truth had never been disproved, and that although there were several distinguished men who had not adopted it, there were also many others equally distinguished, some who formerly were opposed to it, who now gave it their entire support. He would not therefore weary them with the arguments which could be adduced in its favour, as they had already been set forth at length by abler hands than his.

Professor Arnold then dealt with the Report itself, and first pointed out that the steels received were abnormal, but that had already been demonstrated in the remarks on Table 1 (page 24), and the bar which he specially referred to was marked *abnormal* in that Table. Professor Arnold said that specially prepared pure steels and not ordinary commercial steels should have been used for the purposes of the Report, but had such steels been used, he felt certain that he would have been the first to have raised objections to experiments made on a metal which was not a commercial product. As Mr. Stead had stated, the samples of steel were manufactured in the ordinary way by a firm of high standing in Sheffield, and the whole series must be regarded as excellent, so that he thought it was clearly evident that Sir William was perfectly justified in using them for his experiments. As regards the term "maximum stress," the use of which he advocated, that had been disposed of by Professor Unwin (page 125). He was gratified to find that these were the only points in the Report to which Professor Arnold took objection.

The final sweeping statement, which however on reflection he would doubtless have qualified, that if once steel became brittle mechanically it was only fit for the scrap-heap, was most surprising, and was disproved daily in the rolling-mills of tin-plate and other works.

Referring to Mr. Hadfield's remarks (page 122), the steel bar tested at -180° C. (-356° F.) and found to possess such extraordinary physical properties might, he thought, be regarded as another allotropic form of iron and tended to suppose the allotropism of iron rather than to contradict it. As regards the $0 \cdot 18$ per cent. carbon steel in Table 2 (page 26) the mechanical tests had been repeated by Professor Unwin, and he had found the breaking strain to be 33·24 tons per square inch, and the elastic limit to be 26·62 tons per square inch, which practically confirmed the results given in the Report.

Then, as to the statement (page 47): "It is well known that imperfect quenching sets up internal strains in steels which are not entirely eliminated by subsequent annealing, owing to the variation in the density of the metal throughout the mass," he might add that in a mass of steel of comparatively small size—for example, a coinage die for dollars—no system of quenching, even in water, would make it of uniform hardness. This was proved by the fact that such dies when tempered always sank in the middle after a certain amount of work. In larger masses, as axles or gun tubes, this imperfect hardening must be much more pronounced. The quenching of the outer layers of the mass was more rapid than that of the interior, and in consequence of that there must be differences of density in different parts, and hence internal strain. And these strains were not altogether eliminated by the subsequent tempering. Hence the importance, as far as has been pointed out in the Report, of endeavouring to obtain in a steel by annealing the properties possessed by one which had been quenched in oil and tempered.

Dr. Carpenter had asked (page 129), in reference to the Fifth Report, presented in 1899, whether cooling curves were taken of the steels in one of the experiments. In reply, he might say that both ordinary and differential cooling curves were taken, but only the latter were published. The point Ar 0 was discovered, and that would probably indicate a structural change in the ferrite which would doubtless result in a modification of the mechanical properties of steels cooled from 600° C. (1,112° F.). The other points in Dr. Carpenter's remarks have already been dealt with by Mr. Merrett (page 141).

He entirely agreed with all that was said by Sir William White (page 129), and desired especially to support his suggestive remarks as regards work on larger sections, that there could be no doubt about their great value, or that they could be best carried out by manufacturers in their own works under the direction of their scientific staff.

In conclusion, he wished again to thank the members and others who had attended the meetings for the very favourable reception they had accorded to the Report.

The PRESIDENT said he was sure the members would consider Professor Gowland's very able and dignified reply was a worthy ending to the extremely interesting Report and the discussion that had followed. The present was the third evening to which the discussion had extended, and he had pleasure in informing the members that the Council had decided to follow the researches still further. Words were used in the reply which showed that Professor Gowland himself thought they were only on the fringe of the subject, but now they had got very near home with the pure iron and industrial mild steel. The Council had re-appointed the Alloys Research Committee to carry on their work with the co-operation of the National Physical Laboratory. He had no doubt that the National Physical Laboratory would receive help, as had been mentioned, from others; but Dr. Glazebrook would undertake the responsibility of carrying out the directions of the Committee in regard to further researches, and a vote had been made by the Council towards the expenses that would be incurred at the National Physical Laboratory in prosecuting the researches. He wished to say that members of the Institution who had encountered in their practice difficulties due to the occasionally unexpected behaviour of industrial steel, and who would be kind enough to communicate to the Secretary the direction in which they thought it would be useful to carry out the researches, would have their communications welcomed and passed on to the Committee, who would be pleased to receive such suggestions. The vote of thanks to all concerned in the production of the notable Report which had been discussed was passed two meetings ago, and therefore no further time need be taken up in repeating expressions of thanks; but he was sure every member felt what a magnificent work had been done by the Institution in stimulating research. Professor Arnold had written a very cordial letter to Sir William White expressing his desire to co-operate, if he might be permitted to do so, in any further investigations.

Communications.

Mr. Thomas Andrews wrote that he was glad to observe that Mr. Hadfield had referred in the discussion to the effect of extreme cold on the physical properties of practically pure iron, when under tensile stress. It might perhaps be of service and interest in this connection to refer to an extensive series of experiments which the writer had made about twenty years ago on the effect of high and low temperatures on the Impact Resistance of Iron Railway Axles. In these experiments which were made on full-sized railway axles, it was found that a reduction of temperature materially reduced the resistance to impact, which confirmed the results of the experiments now made by Professor Dewar and Mr. Hadfield. He also made experiments on the effects of Chilling on the Impact Resistance of Iron Axles, with interesting results. These researches * were at the time awarded a Telford Premium by the Institution of Civil Engineers. Reference might also be made to the Paper on "Effect of Strain on Railway Axles," † which was awarded the Bessemer Premium of the Society of Engineers. The extent of these large scale experiments would be realized when he stated that above 300 full-sized railway-carriage axles were tested to destruction, and that above 300 tons of snow were used for the

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* "The Effect of Temperature on the Strength of Railway Axles." Proceedings Inst., C.E., vol. 87, page 340; vol. 94, page 180; vol. 105, page 161. —"Effect of Chilling on the Impact Resistance of Metals." Proceedings Inst. C.E., vol. 103, page 231.

† Transactions, Society of Engineers, 1895, page 181.

(Mr. Thomas Andrews.)

freezing mixture required during the four winters in which the investigation was in progress. The results of Professor Dewar's and Mr. Hadfield's experiments and those of his own referred to above were opposed to the theories of the allotropists.

He was glad that Professor Arnold in his remarks again brought forward the failure of the theory of Atomic Laws as applied to Iron, which he (Professor Arnold) had demonstrated at the Institution of Civil Engineers in 1894. He might also remark that he himself had made a confirmatory series of experiments on the "Influence of Alloys on the Structure of Gold." * The results he obtained fully confirmed those previously published by Professor Arnold, which were opposed to the theories of the allotropists. The valuable researches made at the Sheffield University College on the influence of vanadium on iron and also the experiments on pure electrolytic iron were certainly not in favour of the allotropic theory.

With regard to the heat treatment of steel, he might refer to the results of a joint research by himself and his son, Mr. Charles Reginald Andrews, on the "Microscopic Effect of Annealing on Steel Rails," which had occupied them for several years in carrying out. This Paper was published in the Proceedings of the Institution of Civil Engineers.† The changes produced in the micro-crystalline structure of steel rails by annealing were very considerable. He had also demonstrated the important microscopical changes of crystalline structure produced by heat treatment in the experiments he had made in annealing the fractured connecting-rod of H.M.S. "Bullfinch," in course of the investigation and report which he was requested to make about four years ago into the causes of that serious naval accident. The results of the above researches were illustrated by high-power micrographs, which showed the very important changes produced by annealing steel at suitable temperatures. He had also during the past twenty years made numerous other investigations on the thermal treatment of metals, and as a result he was satisfied that

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* "Microscopic Structure of Gold and Gold Alloys," *Engineering*, 30 Sep., 28 Oct., 9 Dec. 1898.

† Proceedings, Institution of Civil Engineers, vol. clvi., 1903-4, Part II.

more attention was requisite to this important subject than was at present given to it. The observations on the slip bands shown in Fig. 162, Plate 39, did not appear to be new, as some time ago Professor Ewing and Mr. Rosenhain demonstrated that the slip bands produced by stress rendered manifest the general orientation of the individual crystal grains of a metal.* This effect was also noticed in the case of stressed platinum in a Paper on "The Microscopic Effects of Stress on Platinum,"† by himself and his son. Whilst greatly valuing much of the careful work done by the Alloys Research Committee, he was afraid that some of it had been somewhat depreciated by the apparent attempt to make some facts fit in with the allotropic theory of steel. This was a regrettable part of these most valuable researches. He deeply deplored the loss which the metallurgical world had suffered through the recent death of Sir William Roberts-Austen.

Professor W. F. BARRETT wrote that there was so much new and instructive information in the foregoing Report, and the amount of work done had been so great, that he heartily congratulated the Alloys Research Committee and those upon whom the labour of the experimental work had fallen, for this important addition to one's knowledge. The great practical importance of a careful study of the heat treatment of steel had become more and more evident since the discovery of recalescence in 1873. It was in September of that year that he (Professor Barrett) first published this discovery, and in a Paper in the Philosophical Magazine for December 1873, he stated that the profound molecular changes taking place in iron at a red heat required careful study, as they were likely to be of considerable importance. In that Paper the opinion of the late Professor Tait (who had discovered the remarkable thermo-electric changes occurring in iron and steel at a red heat) was quoted, viz.: "that iron becomes as it were a different metal on being raised above a certain temperature." That some allotropic modification of

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* Royal Society, Philosophical Transactions, 1899, vol. 193, series A, page 353.

† Royal Society, Proceedings, 1902, vol. 70, page 250.

(Prof. W. F. Barrett.)

iron took place at the critical temperature of recalescence seemed therefore very probable, but the idea was, he thought, first suggested by Professor George Forbes, F.R.S., soon after the discovery of recalescence.

Whilst, therefore, there was much to be said on behalf of M. Osmond's theory—adopted by the late Sir William Roberts-Austen, that these assumed allotropic changes played an important part in the hardening of steel by quenching at a red heat—he could not agree with the sweeping statement made at the beginning of this Report. The author stated (page 9) "that allotropic changes in the iron itself are the all-important factors........in the characteristic capacity of steel for being hardened and tempered. If iron had existed only in the α form, it could never have been hardened by quenching; on the other hand, if β and γ iron were alone known, steel could never have been tempered or annealed." He did not know where the experimental evidence was to be found in support of this statement. On the contrary there was a good deal of evidence which showed that other causes must be considered. In fact, the original views of the allotropist as to the cause of hardening had changed, for they now said (page 8) that it was not β iron alone which caused the hardening, but that this was due to a *joint effect* of a system of two components, iron and carbon, in a particular allotropic condition.

The distinguished physicist, Professor Van't Hoff, was quoted as an authoritative supporter of Sir William Roberts-Austen's views, but what Professor Van't Hoff said, in the quotation cited in the Report, was that iron in a particular condition, β iron, was capable of retaining "variable quantities of carbon in the form of a homogeneous solid solution known as martensite, while this property is not possessed by the α modification of iron." This statement, however, was by no means the β iron theory of hardening, so long advocated by Sir William Roberts-Austen. According to that theory as originally stated, iron when raised to a certain temperature, about 850° C. (1,562° F.), indicated by the recalescent point Ar_3, passed from its ordinary soft condition, termed for distinction α iron, into an allotropic form, which Osmond named β iron. The individual molecules of this β iron were asserted to be intensely hard, and retained their adamantine state when suddenly quenched, provided carbon or some element of low atomic volume was present in the iron. The hardness of tool steel was thus attributed solely to this β iron; the carbon merely acting as a sort of police constable, preventing the β iron reverting to its original soft α condition. When cooled slowly the mob of β iron particles was supposed to slip from the grasp of the comparatively few carbon atoms and hence reverted to the α condition, the annealed or soft state of steel being the result. Further, the non-magnetic state of red-hot iron was supposed to be due to the transformation of α iron into β iron. But the temperature at which iron lost its magnetic state was at the recalescent point Ar_2, from 750° to 800° C. (1,382° F. to 1,472° F.), and if β iron were non-magnetic the change to hardening iron should occur here. Furthermore, red-hot iron or steel suddenly quenched should be non-magnetic, but this was not the case, it was magnetic. M. Osmond had replied to this that all the particles of iron did not go into the β state at a red heat, and it was to the presence of some α iron particles among them that the return to the magnetic condition was due. This however was only conjecture. Other even more cogent objections to the allotropic theory of the hardening of steel have been urged by Mr. Hadfield and by Professor Arnold and others.

Quite recently a paper had been published by M. Carl Benedicks on the Electric Resistance of Steel and Iron, which threw some additional light on this subject.* From the experiments of Mannesmann, and the data arrived at by Benedicks, a curve could be constructed showing the solubility of carbon in iron. This curve was reproduced, Fig. 168 (page 154).

The flexure in this curve at about 750° to 800° C. (1,382° to 1,472° F.) showed that here the solubility of carbon in iron suddenly increased, and a corresponding thermal change, or recalescent point, followed from well known physical principles. Now, he quite agreed with M. Benedicks that this curve helped them to form some idea of the cause of hardening of steel. If, for example, they had a steel with 1 per cent. of carbon, on slowly cooling to the air temperature from a red heat (say 800 C°) such steel would contain 0·27 per cent. of carbon in the form of a solid solution. This was the percentage of *hardening carbon* which existed in annealed, or unhardened, iron or steel, and this figure was singularly confirmed by the data which M. Benedicks derived from his experiments on the electric resistance of steel. If on the other hand the steel were raised to say 800° C. (1,472° F.), and then *suddenly quenched*, it would retain in the state of a solid solution the amount of carbon it was able to dissolve at 800° C., which was upwards of 0·5 per cent., and the steel would be hardened. So that the hardness would seem to be due to the remarkable influence on the physical properties of iron exerted by even *a small percentage of carbon in solid solution* rather than to some hypothetical allotropic state of iron, with intensely hard molecules.

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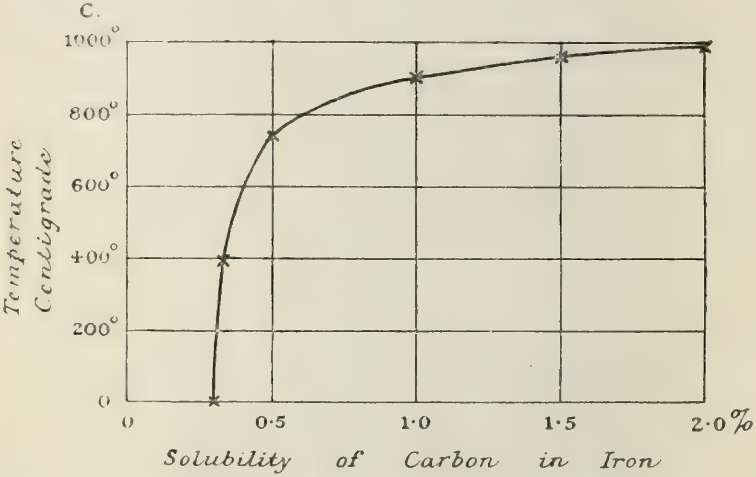
* Zeitschrift fur Physik Chemie, 1902, vol. xl.

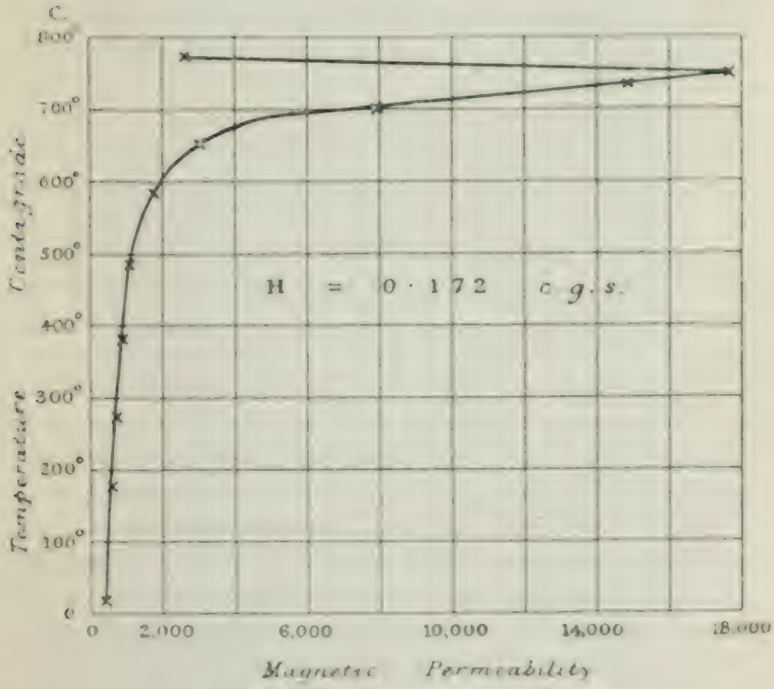
FIG. 168.



This view was supported by the electric resistivity of steel at different temperatures. M. Benedicks had shown, and his (Professor Barrett's) own experiments which M. Benedicks quoted, corroborated the fact that the resistivity of steel increased with its hardness. If therefore the particles of β and γ iron were intensely hard, as assumed by the allotropic theory, one ought reasonably to expect such iron to have a much higher resistivity than the ordinary or α iron, but M. Benedicks found that this assumed β and γ iron possessed exactly the same resistivity as the ordinary α iron.

He (Professor Barrett) did not deny the existence of allotropic forms of iron; their existence might possibly be the cause of the non-magnetic state of red-hot iron and of the thermo-electric and other physical changes that occurred at certain critical temperatures in iron and steel. On the other hand, however, if the non-magnetic state of iron at 800° C. (1,472° F.) were due to a sudden allotropic change, one ought to expect the magnetic permeability of iron to remain constant, or fall off slightly, until this temperature were reached, when a sudden change in its condition would occur.

Fig. 169.



But experiment showed that the magnetic permeability of iron actually *rose* as the temperature was raised, until it reached a maximum not far from the temperature of its non-magnetic state. With very low magnetising forces this increment was very conspicuous, as shown in Fig. 169 (page 155), the result of experiments by a former student of the writer's, Mr. R. L. Wills, B.A.* This was not the place to enter into the changes which in his opinion brought about this result; he proposed to discuss them elsewhere. In any case they had no direct evidence that iron behaved like carbon, and could exist in the *pure state* either as a soft element or as an intensely hard one.

There was one curious fact which had not been considered by the allotropists. Long ago he (Professor Barrett) pointed out that the molecular changes which occurred in nearly pure iron could be as it were "washed out" by repeated heating and cooling. M. Svedelius in an important Paper, the translation of which appeared in the "Philosophical Magazine" for August 1898, had verified this statement, and showed that in a rod of iron containing 0·6 per cent. carbon after being heated and cooled forty times, the magnitude of these molecular changes was reduced nearly one-third; whilst in a rod of electrolytic iron the changes—small to begin with—had entirely disappeared after the fiftieth heating and cooling: no trace of a critical point could then be discovered. The condition of the iron after this treatment showed it to be brittle, with coarse crystalline glossy fracture, and exhibited all the characteristics of burnt iron. Neither could any critical points be found in any specimen of burnt iron examined by M. Svedelius. This Paper, which did not appear to have been referred to by the Alloys Research Committee, was worthy of careful study, for it was in the experimental examination of the various physical changes which occurred in iron at the critical temperatures that they would ultimately arrive at a satisfactory knowledge of the allotropic states of iron, if such really existed.

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* "On the Effects of Temperature on the Magnetic Properties of Iron," by R. L. Wills. "Philosophic Magazine," July 1900.

It was possible that some light might be thrown on this question by means of a series of radiographs taken of a very thin sheet, or film, of pure iron and of steel raised to different temperatures up to 1,000° C. (1,832° F.). In a Paper read before the Royal Dublin Society in March 1896, the writer showed that the opacity of bodies to the X-rays was due to their *molecular weight*, the higher the molecular weight the greater the opacity. But as allotropic states were changes in molecular aggregation, they might therefore expect to find changes in the transparency of iron to the Röntgen radiation when the iron reached certain critical temperatures. He had lately received from Mr. Hadfield some very thin laminæ of steel with which he proposed to try this experiment, though even if changes in transparency were noticed during the heating and cooling of iron, the interpretation of the results would require caution.

Professor E. Heyn, of Charlottenburg, wrote that he was very sorry that he could not be present at the meeting, as the introductory pages of the Report were the last scientific communications left to the world by Sir William Roberts-Austen, to whom science was indebted for a great deal of development and whose death was felt as a heavy loss by all who knew his merits.

As to the subject of the Report, he wished to know how many mechanical tests were made for each kind of steel and each kind of heat treatment. The Report did not give information on this point, though it was one of the greatest importance, since results obtained by testing only a single bar could easily be affected by misleading hazards, and the laws derived therefrom would prove fallacious, especially in the case of hardened steels. He had shown in a Paper* that half-hourly heating of mild steel at temperatures below 700° C. (1292° F.) affected mechanical properties and size of ferrite-grains only, if the steel before being tested was cold-worked, but not if it had previously been annealed. The changes in the ferrite, which

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* Zeitschrift des Vereines deutsche Ingenieure, 1900, vol. 44, page [illegible] "The changes in Iron and Copper in consequence of cold-working, and subsequent heating."

(Prof. E. Heyn.)

were brought about by heating steel, could not only be explained by "slip-bands," but a real growth of ferrite grains took place.

Touching on the subject of the effect of heating steel poor in carbon, especially when soaked at different temperatures, he had pointed out in the Journal of the Iron and Steel Institute in the Paper on "The Overheating of Mild Steel,"* that tensile tests did not give satisfactory information as to the influence of overheating. He had investigated the problem by the use of bending tests on notched-bars. The results gained by this method very clearly showed the laws governing brittleness under varying conditions of temperature and time of heating.

Professor A. LEDEBUR, of Freiberg, Saxony, wrote that he had read the Sixth Report with great interest, and he looked upon it as a worthy conclusion to the admirable work of Sir William Roberts-Austen. While he himself did not agree with M. Osmond's allotropic theory of iron, originally doubting it, similar results of the work also of other investigators, among whom Sir William Roberts-Austen stood in the front rank, had convinced him of the accuracy of the theory that this allotropy played a part in the hardening of steel, if we were not able to support it solely on the results obtained from the hardening. The change of the condition of the hardening carbon and of the iron went exactly together. Iron and carbon retained with hardening the same form that they possessed in red-hot steel, namely hardening carbon and β iron.

Some of the results seemed somewhat remarkable. On Fig. 8, Plate 4, the breaking strain at 0·95 per cent. and 1·3 per cent. carbon was lower than at 0·87 per cent. carbon. The same occurred on Fig. 11, Plate 5; Fig. 15, Plate 7; Fig. 16, Plate 8; Fig. 22, Plate 12; Figs. 26–27, Plate 16. The elastic limit lay particularly low at 0·47 per cent. carbon on Fig. 15, Plate 7; at 0·95 per cent. carbon on Fig. 16, Plate 8; and at 0·25 per cent. carbon on Fig. 17; at 0·72 per cent. on Fig. 24, Plate 14; and at 0·95 per cent. on Figs. 26 and 27, Plate 16. The amounts of elongation and reduction of area were also in many places very remarkable compared with those previously obtained, in contradiction of known variations. He thought that some explanation should be given as to whether any accidents had taken place.

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* Journal, Iron and Steel Institute, 1902, II, page 73.

Mr. **Cecil Lightfoot** wrote that he had recently been giving some attention to the thermal treatment of steel. His investigations so far had been merely of a preliminary nature, but at the same time the following ascertained facts would bear out the suggestion on page 27 of the Report that "annealing of worked bars at temperatures immediately below A_1 may have some commercial significance." He might state that it was the changes taking place between this temperature and the normal with which he had been principally concerned. The exact treatment from which these results were obtained consisted in subjecting the specimens treated not only to a temperature below A_1, but also simultaneously, and during the heating and subsequent cooling, to a uniformly increasing and decreasing fluid-pressure respectively. This pressure was produced by the use of mercury vapour, which was chemically inert towards iron and steel under the conditions of the treatment.

It would be seen that various classes and forms of steel were dealt with.

It was found that :—

(1.) Tool-steel containing 0·55 per cent. of carbon, oil-hardened and annealed in the ordinary manner and tested in tension, possessed an elastic limit of 31·9 tons per square inch, the ultimate stress being 51·7 tons per square inch. On treating similar steel in the manner described the elastic limit was increased to 34·8 tons per square inch, and the ultimate stress to 54·1 tons per square inch. These tests were carried out by Mr. William Kirkaldy.

(2.) Die-forged steel hooks, Vulcan brand, weight 4¼ lbs., as supplied commercially, yielded at a load of about 8,700 lbs. total, and gave out entirely on the load being increased to about 20,000 lbs. When, however, similar hooks were treated as described, they did not yield till the load amounted to 13,200 lbs., the ultimate load being 23,900 lbs. These tests were also made by Mr. William Kirkaldy.

(Mr. Cecil Lightfoot.)

(3.) A sample of ordinary steel-wire 12 B.W.G. when tested showed an elastic limit of 72·4 tons per square inch, and a breaking stress of 90·07 tons per square inch. When treated in the aforesaid manner the elastic limit was increased to 80·87 tons and the breaking stress to 94·01 tons per square inch. These tests were carried out by Professor D. S. Capper and Mr. Henry Waynforth at King's College.

In view of the great amount of time required, and the very numerous experiments necessary, he had not been able up to the present to classify systematically the results obtained by this process, but he merely wished to place before the members a few isolated facts selected from a number of other results of a similar nature. It was with great interest that he had seen that these figures were, to a certain extent, confirmed by the results obtained by the late Sir William Roberts-Austen, as his own figures were obtained entirely with a view to determining the commercial possibilities of such a process.

Captain H. RIALL SANKEY wrote with reference to the closing remarks of Sir William White (page 135) that notched impact tests had been made from 98 test pieces sent to him by Professor Gowland for the purpose; the apparatus, Fig. 170, Plate 43, with which these tests had been made had been fully described in "Engineering."* The test pieces were small, and doubt might arise as to the reliability of such tests, but very numerous comparative trials with test pieces cut out of the same bar of steel had shown consistent results, and it was felt that reliance might be placed on the results of these tests. It was to be regretted that all the tensile test pieces referred to in the Report had not been available, because no doubt interesting results would have been obtained from those belonging to Tables 17 and 18 (pages 66 and 69). Probably the resistance to impact of some of these would have been the highest of any.

In the following Tables were given the results of the impact tests, and the Tables were numbered to correspond with those in the Report.

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* "Engineering," 25 September 1903, page 431.

TABLE 1a (*corresponding to Table 1, page 24*).

(From the Rolls.)

Carbon Per cent.	Impact Test No.	Foot-lbs absorbed by Impact	Description of Fracture.
0·130	—	—	
0·180	5384	12·3	Very fine granular.
0·254	5381	0·8	Very fine granular.
0·468	5385	6·5	50 per cent. very fine crystalline.
0·722	5383	2·8	Fine crystalline
0·871	5382	0·9	Very fine granular.
0·947	5380	0·8	Very fine granular fracture.
1·306	5379	1·3	Crystalline fracture.

TABLE 5a (*corresponding to Table 5, page 34*).

Bars annealed at 900° C. (1,652° F.) for Half-an-hour.

Carbon. Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact.	Description of Fracture.
0·130	5393	15·7	Very tough, not fully fractured.
0·180	5391	0·8	Moderately coarse. Small shiny patches.
0·254	5388	0·7	Moderately coarse. Small shiny patches.
0·468	5392	2·6	Moderately coarse.
0·722	5390	0·9	Moderately coarse fracture. Dull.
0·871	5389	1·1	Close crystalline. With shiny patches.
0·947	5387	0·3	Fine crystalline.
1·306	5394	0·4	Very fine granular.

TABLE 6a (*corresponding to Table* 6, *page* 37).

Bars annealed at 1,100° *C.* (2,012° *F.*) *for Half-an-hour.*

Carbon. Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact.	Description of Fracture.
0·130	5395	0·8	Moderately coarse. Small bright patches.
0·180	5400	0·2	Fine crystalline.
0·254	5396	0·6	Moderately coarse. Bright shiny fracture.
0·468	5402	0·9	Medium coarse. Bright shiny fracture.
0·722	5398	1·0(?)	Coarsely crystalline.
0·871	5397	1·9	Coarsely crystalline. Metallic fracture.
0·947	5399	0·3	Very fine crystalline.
1·306	5401	0·3	Medium coarse. Dull.

TABLE 7a (*corresponding to Table* 7, *page* 39).

Bars soaked at 620° *C.* (1,148° *F.*) *for Twelve Hours.*

Carbon. Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact.	Description of Fracture.
0·130	5407	1·0	Coarse. Bright crystalline fracture.
0·180	5403	0·4	Moderately coarse fracture. Small bright patches.
0·254	5409	0·5	Moderately coarse fracture. Bright shiny patches.
0·468	5406	7·2	Very fine granular.
0·722	5404	2·1	Very fine crystalline.
0·871	5405	0·9	Fine crystalline.
0·947	5408	1·1	Very fine granular.
1·306	5410	0·8	Fine granular fracture. Irregular.

TABLE 8a (*corresponding to Table 8, page 41*).

Bars Soaked at 720° C. (1,328° F.) for Twelve Hours.

Carbon. Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact.	Description of Fracture.
0·130	5415	1·1	Very coarsely crystalline.
0·180	5412	0·7	Moderately coarse. Small shiny patches.
0·254	5418	0·4	Fine crystalline.
0·468	5413	1·0	Fine crystalline.
0·722	5411	0·8	Close crystalline.
0·871	5417	0·4	Moderately coarse.
0·947	5416	0·3	Very fine granular.
1·306	5414	0·4	Fine crystalline.

TABLE 9a (*corresponding to Table 9, page 44*).

Bars Soaked at 900° C. (1,652° F.) for Twelve Hours.

Carbon. Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact.	Description of Fracture.
0·130	—	—	
0·180	5423	0·5	Moderately coarse.
0·254	5420	0·7	Do. do.
0·468	5419	1·8	Close crystalline metallic.
0·722	5424	1·1	Very close crystalline.
0·871	5421	1·5	Fine crystalline.
0·947	5422	0·4	Fine crystalline.
1·306	5425	0·3	Moderately coarse.

TABLE 10*a* (*corresponding to Table* 10, *page* 49).

Bars soaked at 1,200° *C.* (2,192° *F.*) *for Twelve Hours.*

Carbon. Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact.	Description of Fracture.
—	—	—	—
0·180	5428	0·5	Bright crystalline fracture.
0·254	5433	0·5	Crystalline fracture.
0·947	5427	0·9	Bright crystalline fracture.
1·306	5430	0·8	Bright crystalline fracture.
1·306?	5430	2·0	Large light crystals.
(?)	5431	0·9	Bright crystalline fracture.
(?)	5432	1·6	Bright crystalline fracture.

TABLE 12*a* (*corresponding to Table* 12, *page* 55).

Bars quenched at 800° *C.* (1,472° *F.*) *in Water at* 20° *C.* (68° *F.*).

Carbon. Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact.	Description of Fracture.
0·130	5439	3·9	Coarse crystalline.
0·180	5436	5·0	Granular.
0·254	5435	2·1	Very fine crystalline.
0·468	5437	6·7	Granular.
0·722	5438	3·2	Granular fracture.
0·871	5440	2·1	Granular fracture.
0·947	5441	1·0	Very fine granular.
1·306	5442	0·9	Very fine granular.

TABLE 13a (*corresponding to Table 13, page 57*).

Bars quenched at 900° C. (1,652° F.) in Water at 20° C. (68° F.).

Carbon. Per cent.	Impact Test No.	Foot-lbs absorbed by Impact.	Description of Fracture.
0·130	—	—	
0·180	5445	5·5	Fine crystalline.
0·254	5443	2·8	Very fine crystalline.
0·468	5444	3·0	Fine crystalline granular.
0·722	—	—	
0·871	—	—	
0·947	5448	3·0	Granular.
1·306	—	—	

TABLE 15a (*corresponding with Table 15, page 63*).

Bars quenched at 720° C. (1,328° F.) in Oil at 80° C. (176° F.).

Carbon. Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact.	Description of Fracture.
0·130	5452	—	Did not machine up to size.
0·180	5456	10·3	50 per cent. crystalline and 50 per cent. granular.
0·254	5454	2·0	Fine crystalline.
0·468	5458	5·5	Fine granular.
0·722	5451	2·4	Fine crystalline.
0·871	5457	2·2	Fine crystalline.
0·947	5453	1·0	Very fine granular.
1·306	5455	0·7	Fine granular. Uneven fracture.

TABLE 16a (*corresponding to Table* 16, *page* 65).

Bars quenched at 720° *C.* (1,328° *F.*) *in Oil at* 80° *C.* (176° *F.*), *and subsequently reheated to* 350° *C.* (662° *F.*).

Carbon. Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact.	Description of Fracture.
0·130	5459	6·3	Close crystalline.
0·180	5465	7·8	Close crystalline.
0·254	5462	1·7	Very fine crystalline.
0·468	5460	6·5	Granular.
0·722	5461	1·5	Moderately granular.
0·871	5463	1·4	Crystalline.
0·947	5464	2·7	Fine crystalline.
1·306	5467	0·9	Very fine granular.

TABLE 19a (*corresponding to Table* 19, *page* 70.)

Bars quenched at 800° *C.* (1,472° *F.*) *in Oil at* 80° *C.* (176° *F.*), *and subsequently reheated to* 600° *C.* (1,112° *F.*).

Carbon. Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact.	Description of Fracture.
0·130	5473	18·4	Very tough, not fully fractured.
0·180	5472	0·6	Medium crystalline.
0·254	—	—	
0·468	5471	6·8	Granular.
0·722	5470	2·0	Very fine crystalline.
0·871	5474	1·2	Medium crystalline.
0·947	5468	1·7	Granular.
1·306	5469	1·0	Very fine granular. Slightly lustrous.

TABLE 20a (*corresponding to Table 20, page 72*).

Bars quenched at 900° C. (1,652° F.) in Oil at 80° C. (176° F.), and subsequently reheated to 600° C. (1,112° F.).

Carbon, Per cent.	Impact Test No.	Foot-lbs. absorbed by Impact	Description of Fracture
0·130	2482	14·3	Very tough, not fully fractured.
0·140	2476	1·9	Fine crystalline.
0·204	2483	4·0	Fine crystalline.
0·488	2481	2·3	Fine crystalline, 10 per cent. granular.
0·472	2478	1·3	Fine crystalline.
0·571	2480	1·8	Fine crystalline.
0·847	2479	1·0	Fine crystalline. Very fine crystalline.
1·306	2477	0·8	Fine granular.

The impact method of testing was still in its infancy, and required standardising before results could be quoted in a definite form; it was therefore useless to do more than broadly sketch conclusions which appeared derivable from the results given in the foregoing Tables. In the first place no definite relation appeared to exist between the impact figure and the other mechanical tests (breaking stress, elastic limit, elongation and reduction of area) or even a combination of these figures. This was illustrated in Fig. 171 (page 168), in which all the tests given in the Report and the impact figures for the 0·130 per cent. carbon steel were plotted. It would be further seen that the heat treatment had a greater effect on the impact figure than on the other mechanical tests, and this was an important point, because the impact test would thus provide a simple workshop test for verifying whether a specified heat treatment had been carried out or not. As a confirmation of this matter, the following test was quoted which had been made with some mild steel suitable for studs, Table 21 (page 169).

Fig. 171.

Comparison of the Ordinary Mechanical Tests given in 12 Tables of the Report with the Impact Figures for 0·468 per cent. Carbon.

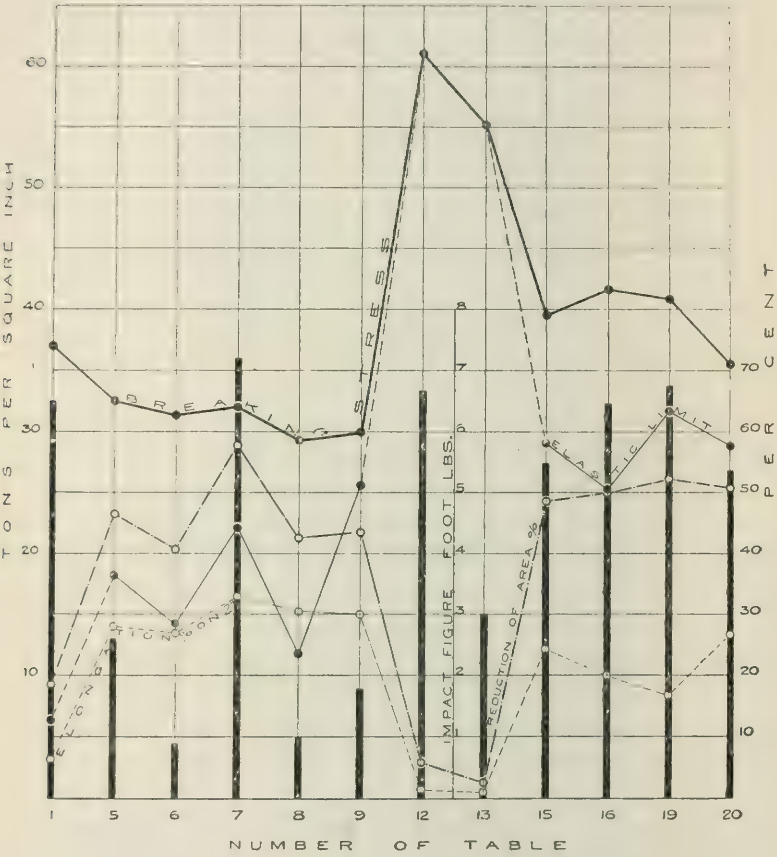


TABLE 31.

Description.	Test Piece No.	Treatment	Yield Pt. Tons per sq. inch.	Ult. Stress Tons per sq. inch.	Elongation on 2 inches.	Reduction	Remarks	Impact Test.	
					Per cent.	Per cent.		Test Piece No.	Absorbed Ft.-lbs.
Steel Steel	[illegible]	Unannealed	22·1	33·3	21·0	52	Very Fine Granular Fracture.	[illegible]	1·8 Short.
	[illegible]	..	21·6	31·7	21·5	52	Do. Do.		
	[illegible]	Annealed	20·8	29·1	33·0	64	Do. Do.	[illegible]	21·2 Very tough Not fully fractured.
	[illegible]	..	21·4	28·1	30·5	58	Do. Do.		

(Capt. H. Riall Sankey.)

The photographs of the test pieces, Fig. 172, Plate 43, bore out the figures given in Table 31 (page 169), which showed a great improvement in the impact figure due to annealing, and comparatively small differences in the other tests.

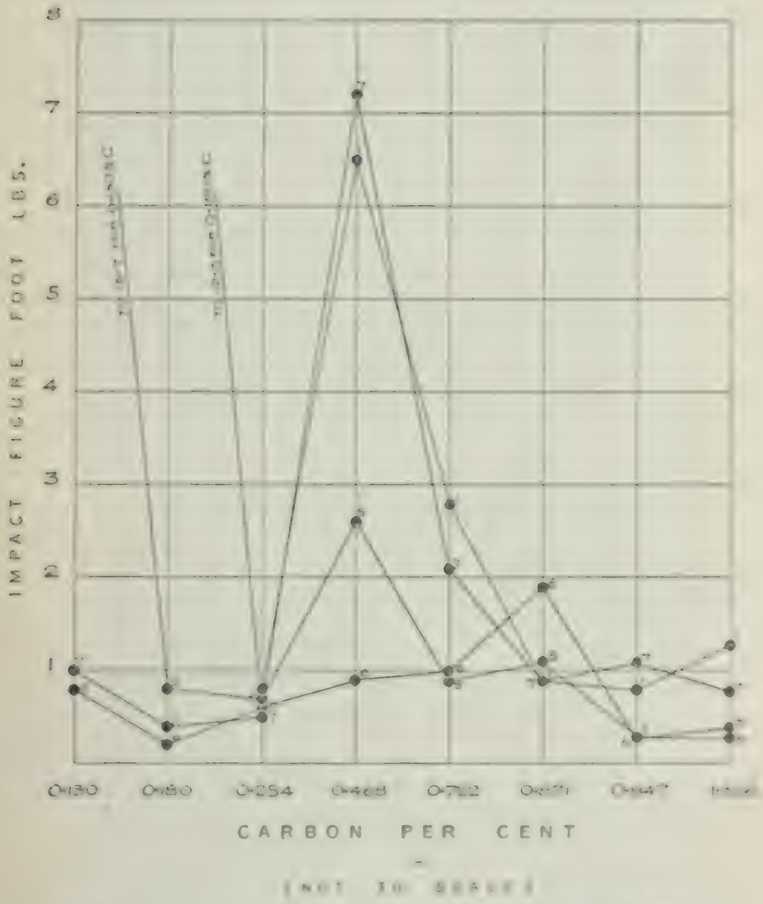
As might be expected, the high-carbon steels showed but little resistance to impact; the very low-carbon steel (0·13 per cent. carbon) had, however, in general considerable resistance to impact (*see* Tables 19*a* and 20*a* for instance). Neither of these classes of steel was used in machinery for the parts in motion, and it was for steels used in such parts that impact tests were of real value. The interest in impact tests really therefore applied to steels containing from 0·2 to 0·5 per cent. of carbon, and it was important to notice in this connection, as would be seen by referring to Fig. 173 (page 171) and Fig. 174 (page 172), that in every case the 0·254 per cent. carbon steel gave a low impact figure, whereas the 0·468 per cent. carbon steel gave a good figure except where the steel had probably been structurally ruined by the heat treatment, as for instance in the case of Tables 8 and 9. A glance through the various Tables in the Report would show that steel of this carbon-content gave on the whole excellent tests for the requirements of Mechanical Engineering. This at present was not the usually accepted view, although undoubtedly of late there had been a tendency to use steels for mechanical purposes of a higher carbon-content than previously. He (Captain Sankey) thought an important point was thus raised, and he would suggest that a study, from this point of view, of steels containing from say 0·2 to 0·5 per cent. of carbon might be undertaken by the National Physical Laboratory with great benefit to the profession.

The notched impact tests had a value beyond the mere figure given as the resistance to impact. The nature of the fracture varied enormously, and it only required greater experience and a codification of the fractures to make the appearance of this fracture a good guide as to the quality of steel, in a manner somewhat similar to the use of micrograph sections; in fact, on comparing the impact fracture with the micrograph sections published in the Report, a relation appeared to exist between the two. The number of comparisons, however, was insufficient to do more than suggest the desirability of continuing research in this matter.

FIG. 175.

Comparison of Impact Figures for Various Steels

(Tables 1 to 7.)

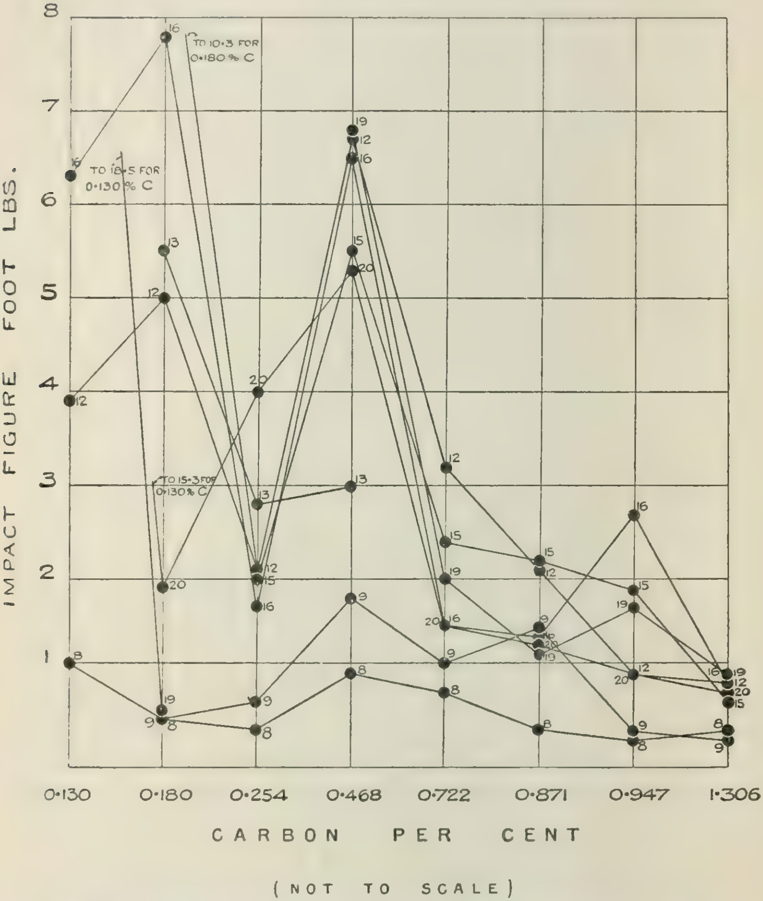


The figure against each dot is the number of the corresponding Table.

Fig. 174.

Comparison of Impact Figures for Various Steels.

(Tables 8 to 20.)



The figure against each dot is the number of the corresponding Table.

Professor GOWLAND wrote that the contributions to the discussion as communicated by writing required but few remarks. Professor E. Heyn, of Charlottenburg, wished to know (page 157) how many mechanical tests were made for each kind of steel and each kind of heat treatment. In many cases only one bar was submitted to each treatment, but in instances where the results obtained were obviously incorrect, other bars were treated in a similar manner and again tested. As had already been pointed out in this Report these tests were simply preliminary ones, and were intended to act merely as a guide in conducting the more extended experiments on larger bars which Sir William Roberts-Austen intended to make later. As the work of the Alloys Research Committee had now been undertaken by the National Physical Laboratory, these researches would doubtless be continued at that Institution.

Professor Ledebur (page 158) called attention to several results in the mechanical tests which were somewhat remarkable; they were nevertheless the results which were obtained, and in some of the more important cases the tests were repeated and the numbers confirmed.

As regards those of Fig. 8, Plate 4, it was shown in the Report that the bars were abnormal in character; explanations were also given under the various Tables of most of the results to which he referred. It must be remembered too that steels of the purity and low manganese content as these bars had been the subject of but few experiments, so that there was no extended series of results with which to compare them in order to determine always which were abnormal, and of course comparison with steels of different composition was inadmissible.

The tests so kindly undertaken by Captain Sankey of the bars which were available undoubtedly threw considerable light on the power a specimen of steel had of resisting shock.

The specifications of gun, axle, and other steels in vogue at the present day had so far not included this method of testing. Reference to Table 9 (page 44) of the Report and to Table 9a (page 163) in Captain Sankey's remarks clearly showed that, although the bars soaked at 900° C. (1,652° F.) for 12 hours gave highly satisfactory results as

(Professor Gowland.)

regards breaking strain, elastic limit, reduction of area, and elongation, yet under the "shock" test it was found that such bars would be totally unsuited for purposes which the above properties should indicate, according to present specifications. The impact tests performed by Captain Sankey were doubtless of the greatest possible importance, and it was to be hoped that this method might be standardized, so that it might be brought into general use.

It had further been shown by Captain Sankey that the fractures obtained by this test were invariably in close agreement with the micro-structures, so that by experience it would not only be possible to learn much respecting the power a steel has of withstanding "shock," but also its previous thermal treatment and carbon contents.

For many years a crude form of impact testing by means of a falling weight has been in vogue for rails, axles, and occasionally for structural steels, but for this purpose a considerable quantity of the metal was required in order to carry out the test.

From the figures indicated in Captain Sankey's remarks, it would appear that tests on such a large scale were unnecessary, and that more useful information could be obtained from a number of small pieces taken from different parts of a mass of metal than from a single large piece. A series of impact tests on various classes of steel, which had been submitted to different forms of thermal treatment, would be invaluable to engineers, and he strongly endorsed the view of Captain Sankey that a careful study should be made of steels containing from 0·2 to 0·5 per cent. of carbon. He also hoped that these researches might be undertaken by the National Physical Laboratory.

APPENDIX I. TO SIXTH REPORT TO THE ALLOYS RESEARCH COMMITTEE.

THE CONSTITUTION OF METALLIC ALLOYS.[*] (ALLOYS CONSIDERED AS SOLUTIONS.)

By the late Sir WILLIAM C. ROBERTS-AUSTEN,
K.C.B., D.C.L., D.Sc., F.R.S., *Honorary Member*,
and Dr. ALFRED STANSFIELD.

Introduction.—When the study of chemistry began to make rapid progress, in consequence of the discovery by John Dalton in 1803 of the laws of combining proportions and his enunciation in 1808 of the atomic theory, the attention of chemists was specially directed to the investigation of the nature and properties of such bodies as salts, in which the connection with the atomic theory was most clearly evident.

As the metallic alloys lie on the borderland between the provinces of the chemist and of the physicist, they were not unnaturally much neglected in these early days, and when, in the course of time, their study was seriously undertaken, the atomic theory appears to have retained an undue place in the minds of successive experimenters.

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[*] Being a reprint, somewhat summarised, of their Report to the Physical Congress, Paris, 1900. This was handed in by the Authors in October 1901.

It was not until physics had further developed, and the nature of solutions had been more fully investigated, that a correct estimate of the constitution of metallic alloys became possible. It is now recognised that experiments on the nature of molten and solid alloys will materially advance our knowledge of the constitution of solutions generally.

Methods of Investigation.—The study of alloys, from the point of view of the chemist, has been found to be difficult because their constituents do not combine simply in atomic proportions. The physicist has, in turn, found the study difficult because the opacity of metals and alloys precludes the use of optical methods, except in a few instances. Alloys, moreover, do not conduct electrolytically, and thus a whole field of investigation has hitherto been closed.

In consequence of these difficulties, the methods of investigation that have been adopted are mostly indirect ones. Almost every physical and chemical property of metals has been utilised in their study. Speaking generally, it may be said that efforts have been directed mainly with the intention of determining—

1. The various groups or compounds which constitute the solid alloy. In this connection the chemical composition, the relative amounts, and the distribution of each group that may be formed, have to be ascertained.
2. The conditions under which certain constituents or groups crystallise or separate from the molten alloy during solidification, and what molecular or other changes take place during the subsequent cooling of the metallic mass to the ordinary temperatures.

When full information under these two heads has been obtained, it will be possible to consider what was the constitution of the alloy while it was still molten. It may be viewed as a solution of the constituent metals, together with any chemical compounds that may be formed. The changes which occur on solidification, and the extent to which the metals remain in mutual solid solution, can then be considered. The information necessary for answering the above questions has been sought for in a large number of ways, and may be considered under two distinct heads.

(A) *The Chemical Grouping of Metals in a solid Alloy.*—The experiments made with a view to determine the grouping of the constituents in the solid alloy involve the following methods and subjects of research, which are considered in detail in the original paper:—

(*a*) Microscopic examination of a polished and etched section of the alloy.

(*b*) Isolation of the constituents of the alloys by suitable chemical solvents, with or without the aid of an electric current.

(*c*) The electromotive force of solution of metals and alloys.

(*d*) The electrical resistance of metals and alloys.

(*e*) The specific gravity of alloys.

(*f*) The heat of combination of metals to form alloys.

(*g*) The thermo-electric power and the Volta effect.

(*h*) Metallic diffusion in liquid and solid alloys.

(*i*) Metallic conduction of electricity and the difference between this and electrolytic conduction.

(B) *Separation of the Constituents during Solidification.*—The conditions under which the several constituents separate from the molten alloy during solidification and the existence of any subsequent molecular changes have been studied.

(*j*) By means of the pyrometer, especially the thermo-couple with recording apparatus.

(*k*) By heating the alloy to definite temperatures and separating by pressure the liquid from the still solid portion, both of these being analysed.

(*l*) By investigating the changes in the magnetic character of steel and other magnetic alloys, as they are heated or cooled.

Classification of Metallic Alloys.

Metallic alloys are commonly known in two out of the three states of matter, namely the solid and the liquid. The gaseous state of alloys has not yet been studied to any great extent, and may for the present be omitted, but it may be added that native alloys are found which have evidently been formed by the condensation of metallic vapours, and this also applies to certain metallic furnace products. Although alloys are of more industrial importance in their solid than in their liquid condition, it will be well to consider first their constitution when molten, because, with a few important exceptions, which will be dealt with later, all alloys have passed through this state, and their solid condition can only be fully explained as an outcome of the preceding molten condition.

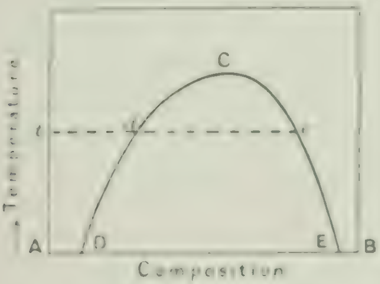
Liquid Alloys.—So far as we are aware, the constitution of a molten alloy is quite independent of the state of aggregation of the alloy, or of the constituent metals in their previous solid condition. Alloys when molten consist, as has been already stated, of one or more mutual solutions of the constituent metals, and of any definite compounds that may be formed. Consideration will first be given to the comparatively simple cases in which no chemical compounds are formed, and we will also limit the consideration at first to binary alloys. In such an alloy each metal dissolves a certain amount of the other metal, until it is saturated with it, two conjugate solutions being, in general, thus obtained which may be mechanically mixed so as to form an emulsion, or may separate into two layers in virtue of their different specific gravities.

The solubility of each metal in the other is a function of the temperature. This is clearly shown in Fig. 175, for the alloys of two metals A and B. The ordinates denote the temperature of the molten alloy, and the abscissae the percentage of the metal B present in each solution.

At the temperature *t*, for example, the two conjugate solutions would contain *td* per cent. and *te* per cent. respectively of the metal B, and any alloy containing more than *td* per cent., and less than *e* per cent. of B would at this temperature consist of a mechanical mixture of these two conjugate solutions. At higher temperatures the solubility of each metal in the other increases, until at C the metals finally coalesce to form a single solution.

Any alloy may be represented as regards composition and temperature by a single point on the diagram. If the point lie within the curve DCE, two conjugate solutions will be found, but if outside the curve only one solution can exist, DCE has consequently been termed the "critical curve." In the case of ternary alloys three separate solutions may result, and this can be indicated by means of an equilateral triangle. (See original Paper.)

Fig. 175.



Solid Alloys.—Leaving entirely on one side the mode of formation of solid alloys, it can be shown that they may be classified in exactly the same manner as fluid alloys. Thus two or more metals will dissolve in one another and will form a solid solution precisely analogous to a liquid solution. The limits of temperature and composition within which solid solutions can be formed may be indicated exactly, as in the case of liquid solutions, by the critical curves dividing the regions of complete miscibility from those of two or more conjugate solutions, Fig. 175, and it will therefore not be necessary to repeat what has been already stated about the liquid metallic mixtures.

The mutual solubility of solid metals is, however, usually much less than that of liquid metals, hence the well known fact that solid alloys are less frequently homogeneous than liquid alloys. It follows that a knowledge of these limits of solubility in the solid state is of far more importance than in the liquid state. The study of solid metallic solutions is, however, more difficult than that of liquid solutions, because the condition of equilibrium, so readily attained in the case of liquids, requires, in the case of solids, an interval of time which may amount to days, years, or centuries before it is even approximately established. This arises, of course, from the very limited movement of the molecules in a solid, but it must be remembered that while it adds enormously to the difficulties of the investigation, there is no essential difference between the liquid and the solid solutions. Even in liquid solutions, a certain time must elapse before equilibrium is established, and the change to the solid state merely prolongs this time. The diffusion of gold in solid lead * at temperatures varying from 15° C. (59° F.) to 250° C. (482° F.) may be cited as an instance. Under the conditions of the experiment, there were no indications that equilibrium had been attained between the solid gold and its solution in solid lead. On the other hand, in the cementation of iron to form steel, there is a well-recognised limit, which increases with the temperature, beyond which no more carbon will dissolve in the iron.

The essential point to be remembered in applying existing knowledge of liquid solutions to solid alloys is that there are definite laws of solubility for solids as for liquids, but that if the solids are brought merely into mechanical contact, an exceedingly long time must elapse before equilibrium can be established. On the other hand, when a liquid alloy solidifies, the solid must have been in equilibrium with the liquid at the moment of its formation, and this greatly facilitates the study of solid solutions.

Changes from one state of matter to another.

(a) *From the state of vapour to that of liquid or solid.*—Very little is known about this in the case of alloys, though, as has already been stated, alloys condensed from vapour are known. Metals in the state of vapour being completely miscible, liquid or solid alloys will form from them according to the amount of each metal present in the vapour and to the vapour pressure exerted by each constituent of the solid or liquid alloy which is formed. The alloy will form in the liquid or the solid state according to the temperature (and to a very slight extent the pressure) at which the condensation occurs. It is possible in this way to form certain solid alloys by condensation of vapour without passing through the liquid state, and it would be interesting to determine whether the structure of an alloy so formed would be similar to that of an alloy which had been produced by fusion. Mond's Nickel, prepared by deposition from the gaseous nickel-carbonyl, is really an instance of this, as an alloy of nickel and iron may be obtained in this way from mixed nickel and iron carbonyls.

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* Roberts-Austen. Philosophical Transactions Royal Society, 1896, vol. 187, series A, page 386.

FIG. 176.

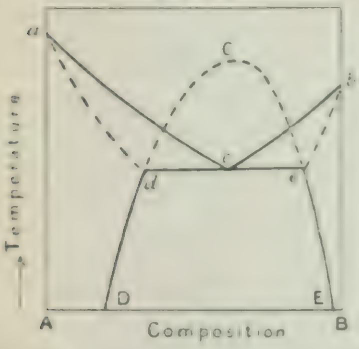
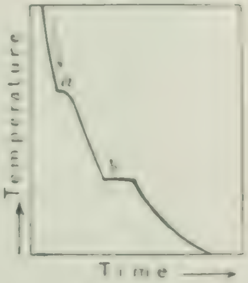


FIG. 177.



(b) *Changes from the liquid to the solid state.*—Although fluid alloys may be very complex, the mutual solubility of the metals is in general so great that a single solution is alone produced. It will be well to consider this case first, and to begin with the consideration of alloys in which no chemical combination takes place. In alloys of this class it is usually found that the temperature of solidification of each metal is lowered progressively by successive additions of the other metal. This is indicated in Fig. 176, where the abscissae denote the proportion of the two metals A and B in the alloy, and the ordinates denote the temperature. *a* and *b* are the melting points of the pure metals, and the melting points of the intermediate alloys are represented by the lines *ac* and *bc*, which meet and form an angle at *c*.

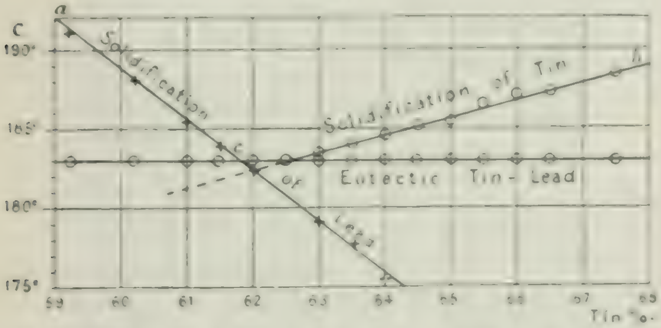
The determination of the temperatures of solidification of a series of alloys is most readily effected by taking an autographic record of the rate of cooling of each alloy of the series. Such a cooling curve for an alloy of this class is represented in Fig. 177 (page 181) in which ordinates denote the temperature, and abscissae time. It will be seen that there are two breaks in the curve, one at *a*, where the curve abruptly changes its direction and then gradually resumes it again, and another at *b* in which both the beginning and the end of the change are sharp.

The angle at *a* denotes the beginning of the crystallization of the metal which is in excess in the alloy, and which may be called A, the change of direction being produced by the evolution of the latent heat of solution. As the metal crystallizes, the remaining liquid contains less of the metal A, and the temperature of saturation falls. It follows from this that no part of the curve at *a* can be quite horizontal, and that it must gradually become more and more inclined, and as the liquid becomes poorer in the metal called A, a point is reached when it becomes saturated also with the metal B; from this point the metals A and B solidify side by side, the residual liquid remaining of the same composition, and consequently at the same temperature, until the whole has solidified. This stage of the solidification of the alloy is represented by the flat part *b* of the cooling curve in Fig. 177. The temperature of the first break in the cooling curve varies in the different members of the series, as is shown by the line *a c b*, Fig. 176, but the temperature of the second stage is constant in all the alloys of the series, in which this arrest can be detected. This is indicated in Fig. 176 by the horizontal line through *c*.

For the sake of simplicity the metals A and B have been spoken of as crystallizing in the liquid alloy, but it must be remembered that each of these metals crystallizes with a certain amount of the other dissolved in it, forming a solid solution, the degree of concentration of which depends on that of the liquid solution from which it separated. This is indicated in Fig. 176 by the dotted lines *a d* and *b e*, which show for each temperature the composition of the solid solutions that can be formed. It will be seen that the degree of concentration of the solid solution bears a general relationship to that of the liquid solution from which it was formed, and it may be assumed for the present that in the case of dilute solid solutions they are simply proportional.

The points *d* and *e*, at which the lines of solid solution meet the eutectic line, represent solid solutions which are in equilibrium with each other and with the liquid alloy *c*. They are in fact saturated solutions, and give two points on the curve of mutual solid solubility D C E. It may then be said that a solidified eutectic alloy consists of a mechanical mixture of two saturated or conjugate solid solutions.

FIG. 178.



It should be remembered that there is nothing fundamental about the composition and temperature of the point *c*: it is merely the point of intersection of the lines *a c* and *b c*, either of which might have been prolonged in the absence of the other. This had been investigated in the case of salts, and has lately been experimentally realised by us,* in the case of the tin-lead alloys, by utilising the phenomenon of selective surfusion.

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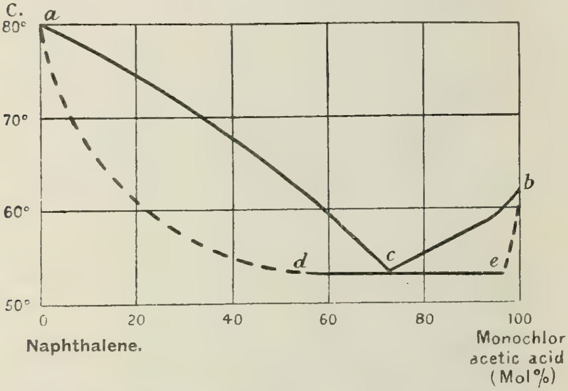
* Roberts-Austen. Proceedings Royal Society, vol. lxiii (1898), page 112.

Fig. 178 (page 183) shows a portion of the "freezing-point curve" of the lead-tin alloys, in which the line *a c* has been traced in this manner to a temperature 7° C. (12·6° F.) below that of the eutectic freezing point, and 9° C. (16·2° F.) below that at which the tin should have commenced to crystallize.

Now if, as has been shown, the line *a c* can be prolonged, it is obvious that the line *a d* in Fig. 176 (page 181) can also be prolonged to some point within the curve D C E, and it might be thought that the solution *d* could not really have been saturated. That this is not the case will be evident when it is remembered that the presence of the conjugate solid *e* would lead to a re-arrangement of the dissolved metals. The prolongation of *a d* merely represents a condition of supersaturation analogous to that of surfusion.

FIG. 179.



In order to plot the curves of solid solution *a d* and *b e*, it will be necessary to separate mechanically the crystals from a cooling alloy, and to determine their composition. Unfortunately very little work has been done in this direction, although Matthiessen,* so long ago as 1867, published the results of some experiments on the composition of the crystals which separate in gold-tin alloys. The authors are therefore unable to present any example of a metallic alloy in which the composition of the solid phase has been experimentally determined; but we can, as will be explained later, gain some information as to the composition of the solid phases from the shape and degree of curvature of the equilibrium curves *a c b*. In the meantime, as an example, may be given the solution curves of mixtures of naphthalene and monochlor acetic acid, Fig. 179, which have been investigated by Cady;* the figure has been lettered to agree with the typical case in Fig. 176 (page 181), but the curve D C E has been omitted, as sufficient data for its construction were not available. Fig. 176 may be considered as representing the solidification of the typical binary alloy, in which no definite compounds are formed, and the investigation of cases which may be regarded as modifications of this type may now be taken in hand, these modifications resulting from the greater or less degree of mutual solubility of the solid metals.

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* Matthiessen, Journal Chemical Society (1867), page 201.

Fig. 180.

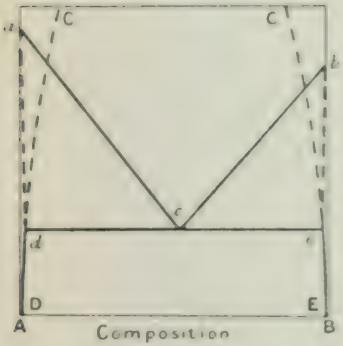
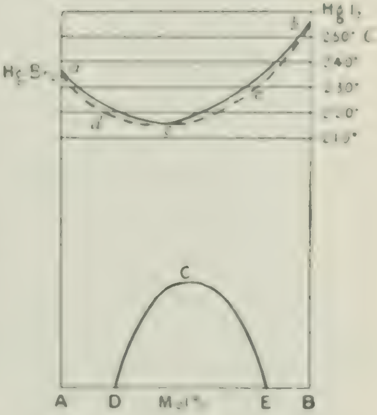


Fig. 181.



In Fig. 180 is presented the case that has generally been contemplated by writers on alloys, that, namely, in which the mutual solubility of the solid metals is so slight that they may be regarded as being practically insoluble in one another. The crystals which separate on the lines *a c* and *b c* consist of the pure metals A or B, and the eutectic alloy is also an intimate mixture of the pure metals. The curves *a c* and *b c* can consequently be represented by the equations of Van 't Hoff * or of Le Chatelier,† both of which require the separated metal to be pure. The curve D C E, denoting the mutual solubility of the solid metals, must be drawn in such a manner as to practically coincide with the lines A*a* and B*b*. The

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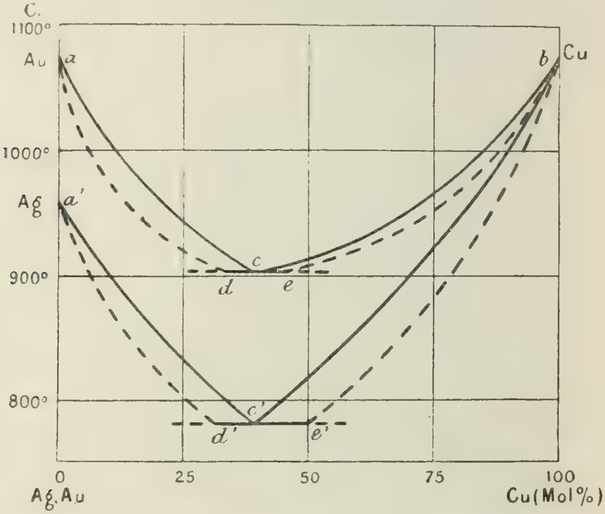
* Cady, Journal of Physical Chemistry (1899), vol. iii. page 127.

FIG. 182.



branches D C and E C may meet as in the typical case, Fig. 176 (page 181), but it will be at a very much higher temperature. The upper parts of these curves are indicated to show the continuity between the different classes of alloys, only those parts below *d e* being generally realised.

If an alloy is now considered in which the solid metals are more soluble in one another than they were in the typical case, it may be found, as in Fig. 181 (page 185), that the curve *a c b* lies wholly above D C E. In other words the metals A and B are completely soluble in each other, and the solid solution which is formed changes gradually and without any discontinuity from one pure metal to the other. This gradual transition is indicated by the dotted line *b c d a*, and it follows from this that the equilibrium curve *b c a* must also be continuous, the angle at *c* having been quite obliterated. The upper part of Fig. 181 represents the temperatures of solidification of fused mixtures of mercuric iodide and bromide, and the compositions of the solid solutions which are formed. The curves were taken from a recent Paper by Reinders,* and were selected as an example because the composition of the solid phase had been determined.

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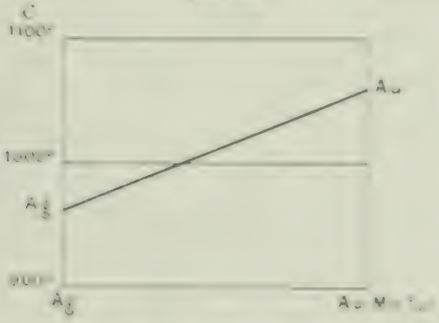
* Van 't Hoff, Philosophical Magazine, 1888, vol. xxvi, page 81.

† Le Chatelier, Annales des Mines, 1888.

Fig. 182.



In Fig. 182 are given the equilibrium curves of the gold-copper and the silver-copper series of alloys recently obtained by one of the writers.†

The silver-copper alloys may be given as an illustration of the typical case, Fig. 176 (page 181), and the gold-copper alloys serve very well to illustrate the transition from this to the special modification presented in Fig. 181 (page 185); the angle at *c* being almost obliterated by the increased curvature of the branches. The dotted curves giving the composition of the solid phases are not the results of experiment, as none were available, but have been calculated approximately from the shape of the curves, in a manner to be explained presently.

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* Reinders, Kon. Akad. van Wetens. te Amsterdam, 1900, page 136.

† Roberts-Austen. Mint Report, 1900, page 73.

There is still one more modification of the typical case to consider, namely, that in which the solid phase has nearly the same composition as the liquid from which it separates; under these conditions the temperature is almost constant during solidification, and the equilibrium curve is represented, as in Fig. 183 (page 187), by a straight line Ag Au joining the melting points of the two metals. This line also shows approximately the composition of the separating solid.* It will be seen that such a case indicates a further increase in the mutual solubility of the solid metals, and it may be inferred, although no experiments have been made in this direction, that the critical curve D C E, if it exists at all, must in this case be far below the line Ag Au. The gold-silver alloys,† which are represented in Fig. 183 (page 187), form a very good example of this class.

Alloys whose equilibrium curves are straight lines, as in Fig. 183, or U-shaped curves, as in Fig. 181 (page 185), have been termed "Isomorphous" by some workers; while the term "mixed crystals" has been applied to the solid separating from fused mixtures of salts, when, as usually happens in alloys, the composition of the separated solid varies continuously within certain limits. The use of these terms arises from the different points of view of various workers; and the terms connote certain properties which, as Le Chatelier ‡ has pointed out, are not quite general.

Much would be gained if chemists and physicists could agree to use the term "solid solution" wherever it can rightly be applied, as this would bring so many apparently isolated phenomena into line with one another, and the small change in nomenclature would do much to encourage the application of the laws of liquid solutions to solids.

A mathematical discussion in the original Paper may be summarised as follows:—Formulæ have been given by Van 't Hoff and Le Chatelier for calculating the molecular weight of a dissolved body from the lowering of the freezing point of the solvent. Heycock and Neville have applied these formulæ to the case of metallic alloys, and find that the metals in fluid alloys are in general monatomic, when they do not combine to form compounds. They find, however, that the observed lowering is usually less than the theory demands, and that the difference is more pronounced as the solutions become less dilute. The authors point out that Van 't Hoff and Le Chatelier based their formulæ on the assumption that the pure metal (or a metallic compound) solidified first in a cooling alloy, but that in reality a solid solution is usually formed, and that the formulæ should be modified to recognise this fact. The authors obtained formulæ for the general case in which a solid solution is formed.

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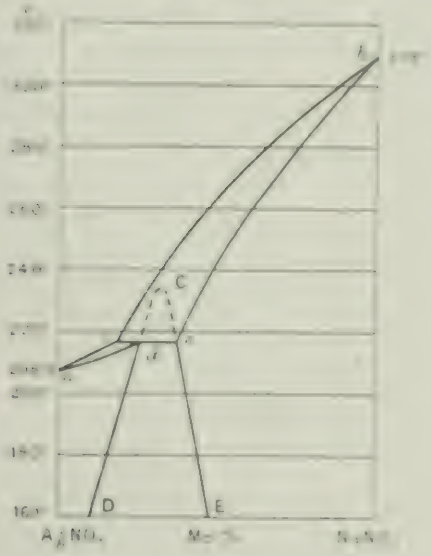
* The composition of the separated solid will probably be represented by a slightly curved line concave upwards and passing through Ag Au.

† Roberts-Austen and Rose, Proceedings Royal Society, vol. lxxi, page 162. They have shown that the freezing-point curve of the gold-silver alloys is not a straight line, as had been supposed, but has a decided curvature, the convex side being up.

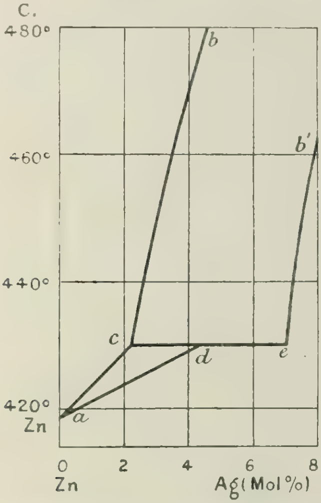
‡ Annales des Mines, 1897.

Fig. 184.



In order to avoid confusion, the consideration has been left until now of a variety of the typical case which might occur if, as in Fig. 184 (page 189), the melting point *a* of one metal were lower than the point *c* at which the line *b e* intersects the curve D C E. Under these conditions the equilibrium curve would consist of two parts, *a c* and *c b*, meeting at an angle at *c*, only *c* is no longer a point of maximum fusibility, and the solid that separates at this temperature is not a eutectic, but a saturated solid solution of B in A.

Fig. 185.



The point *c* has been called a *transition* point, because it denotes an abrupt change in the composition of the deposited crystals. Immediately above *c* these crystals were saturated solutions of A in B, and at *c* they become saturated solutions of B in A.

The authors were not aware of any example of this in the case of simple alloys, though such are constantly met with when metallic compounds are present. Professor Bakhuis Roozeboom has however investigated an exactly analogous solution, namely that of the fused mixtures of silver nitrate and sodium nitrate,* and these are represented in Fig. 184, the whole of which, with the exception of the curve *d* C *e*, is based on experimental data.

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* Roozeboom, Kon. Akad. van Wetens te Amsterdam, Nov. 1899.

In Fig. 185 are given the equilibrium curves of part of the zinc-silver series of alloys,* which are exactly analogous to the case just described. In this series, definite compounds of zinc and silver are formed, and these compounds, as well as the pure metals Ag and Zn, are concerned in the equilibrium. The lines represent the theoretical equilibrium curves and compositions of the solid phase, but as the latent heat of fusion of the compound (assumed to be AgZn) was not known, and was therefore deduced from those of the pure metals, it was not expected that they would be very accurate.

In tracing the solidification of alloys it has been tacitly assumed that equilibrium would *not* be established between the solid phases deposited at the different stages. During the solidification of a metallic alloy solid solutions of varying concentrations are deposited, and, as has been shown microscopically, these are frequently deposited as concentric layers on the same crystal.

Other considerations would be involved, if sufficient time were allowed for these layers to arrive at a state of equilibrium among themselves, and it is only under such conditions that a true equilibrium curve can be obtained.

Solid Alloys containing Definite Compounds.

The existence of definite compounds in alloys has been known for a long time, being inferred from the occurrence of more or less abrupt changes in their physical and in some cases their chemical properties, as their composition was gradually altered. Great difficulty has attended all efforts to isolate these compounds, because they are far less stable than those generally recognised by chemists, being rather of the nature of molecular compounds, like the salts containing water of crystallization. When in the molten state, these compounds are probably partially dissociated into their constituent metals, and it follows from this that we can seldom observe their true point of solidification. Indeed an alloy, made up in the molecular proportion of a compound that undoubtedly exists, not infrequently shows evolutions of heat at two distinct temperatures during solidification.

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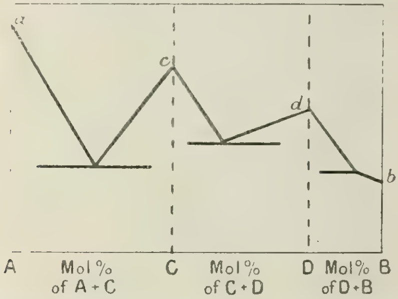
* Heycock and Neville, Transactions Chemical Society, [illegible], page [illegible].

The conditions of equilibrium in the solidification of alloys containing compounds are far more complicated than in the case of simple alloys, but after what has been said about the latter it will be possible to treat somewhat briefly the alloys with compounds.

Fig. 186 represents a series of binary alloys of the metals A and B, in which compounds C and D are formed. If C and D were not dissociated when fused, the diagram might be divided into three parts by vertical lines through C and D, and each of these would represent an independent series of binary alloys with a critical curve and equilibrium curve such as has already been considered. In such a case it would obviously be meaningless to plot the whole diagram in atomic proportions of the metals A and B. Each section must, if molecular plotting be required, be plotted separately in molecular proportions of the virtual components, if all the possible information is to be gained from the shape of the curves.

FIG. 186.

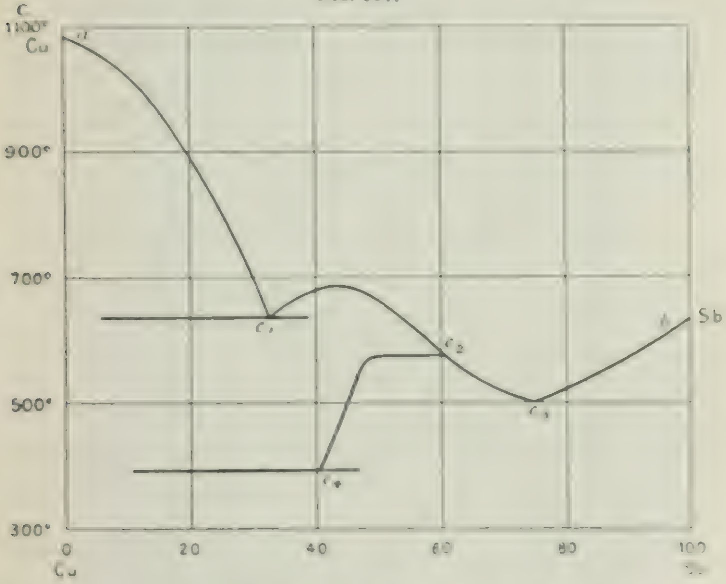


The effect of dissociation of the compounds is to lower their apparent melting points, and to increase the mutual solubility of the virtual solid constituents by increasing the number of distinct substances which take part in each solid solution.

This would be rendered apparent by a rounding of the points *c* and *d* in Fig. 186. The existence of dissociation in alloys usually renders it almost impossible to plot satisfactorily the whole figure in molecular percentages of the various components which are present.

The alloys of antimony and copper, Fig. 187, will illustrate the effect of dissociation; they have only one or two well-defined compounds and eutectic alloys, and in consequence of this the explanation of their curves of equilibrium is comparatively simple. The lines passing through c_2 c_4 are probably not quite complete.

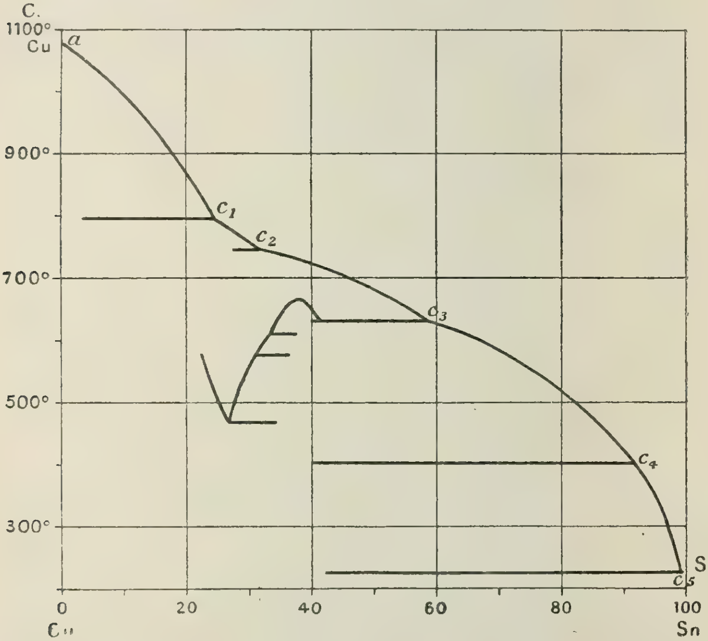
FIG. 187.



In a large number of alloys, chiefly those which are of industrial use, such as the copper-tin and the copper-zinc alloys, the compounds that are found are ill-defined, being largely dissociated when fused, and somewhat soluble in one another when solid. The great fusibility of one of the component metals, together with the imperfect definition of the compounds, has the effect of producing an equilibrium curve which tends continually downwards in passing from one metal to the other. Instead of the eutectic alloys which were so characteristic of the copper-antimony alloys, several transition points are found at which saturated solid solutions are formed.

As an instance of this the series of the copper-tin alloys, Fig. 188, may be taken. The equilibrium curve for this series was first given by one of the writers * in 1895, and more fully in 1897, while Heycock and Neville † have made very careful determinations of the greater portion of the curve. The curve in Fig. 188, which embodies the results of the author's determinations, is plotted in ordinary percentages of copper and tin, and in this form, or when plotted in atomic percentages of copper and tin, it is remarkable for the convex form of the curve descending from the freezing point of pure copper. This form is entirely different from the theoretical curve which should have its concave side upwards, but it can easily be explained

FIG. 188.



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* Stansfield, Proceedings, Institution of Mechanical Engineers, 1895, Plates 41–43; and 1897, Plate 10.

† Heycock and Neville, Philosophical Transactions, Royal Society 1897, vol. 189, series A, page 63.

if it be supposed that the tin which is present in the molten alloy remains in combination with the copper as $Sn\ Cu_4$, and indeed a suggestion to this effect was made by Heycock and Neville. If this part of the curve is plotted in molecular percentages of copper and $Sn\ Cu_4$, remembering that copper has been shown to be monatomic when dissolved in another metal, it is found that the curve assumes a normal shape.

A comparison of the experimental curve in Fig. 188 with the theoretical curve of equilibrium appears to afford strong support to the view that in alloys containing not more than 25 per cent. of tin by weight, some compound of copper and tin, such as $Sn\ Cu_4$, remains to a great extent undissociated in the fluid alloy. Similar evidence renders it probable that brass containing less than 30 per cent. or 40 per cent. of zinc contains undissociated Cu Zn when fluid.

The curves of the copper-tin alloys are remarkable for the complicated equilibrium curves which are found at lower temperatures than the initial curve of equilibrium.

If these curves indicate the solidification of a still fluid portion of the alloy, we must suppose that, as in the lead-copper alloys, conjugate liquid solutions are formed; while, on the other hand, if they indicate the crystallization of substances from a state of solid solution, they will constitute an important field for research into the mutual solubility of solids.*

Solidification of Ternary Alloys which are wholly Miscible when Fluid.—In view of the great complexity of such alloys, and of the relatively small amount of work that has been done in connection with them, it will not be necessary to consider them at any length.

The melting points of a ternary series of alloys may be represented, as Charpy † has shown, by a model obtained by drawing an equilateral triangle to represent the composition of the series of alloys, and erecting a perpendicular at each point to denote the melting temperature. In a ternary series, in which no compounds are formed, and each pair of metals has one eutectic, the eutectics will appear on this model as three valleys, running downward, one from each edge of the triangle, to a common point representing a ternary eutectic which is more fusible than any other alloy in the series. On such a model the existence of metallic compounds would be indicated by mountains rising above the surrounding surface.

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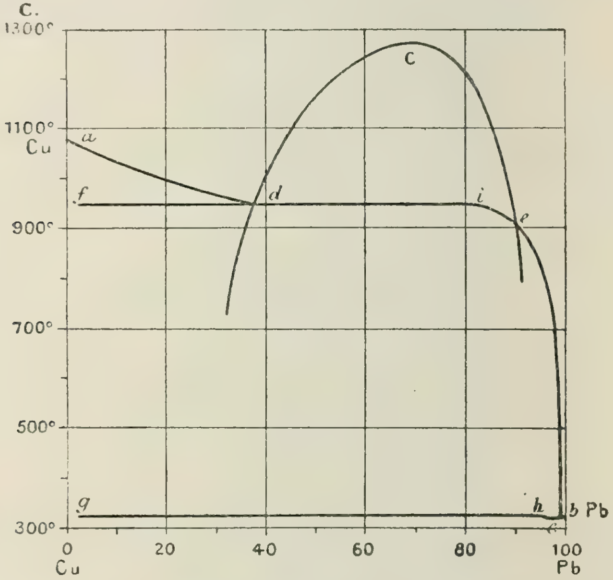
* Since the above was written, Heycock and Neville (Proceedings Royal Society 1901, vol. 68, page 171) have shown that some of these curves indicate crystallization from a solid solution.

† Charpy, Bulletin de la Société d'Encouragement pour l'Industrie Nationale, 5th series, Vol. iii, 1898, page 689.

Fig. 189.



Solidification of Alloys which are not completely Miscible when Fluid.—As an example of this the solidification of the copper-lead alloys may be taken.

The curves of solidification of these alloys were obtained by one of the authors in 1897,* and have been reproduced in weight percentages in Fig. 189. In order to render their meaning clearer, a portion of the critical curve *d* C *e*, showing the liquid miscibility of the metals, has been added, although only one point of this curve has been ascertained with any degree of accuracy.

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* Roberts-Austen, Proceedings, Institution of Mechanical Engineers, 1897, Part 1.

If an alloy is considered lying to the right of this curve, it will be evident that the usual case is presented of an alloy with two branches *c e* and *c b* and a line of eutectic solidification at *h c*. To the left of the critical curve is the equilibrium curve *a d*, and a horizontal line *f d* resembling an eutectic line, but having a somewhat different meaning. During the solidification of an alloy lying in this part of the diagram, solid copper separates, containing perhaps a little dissolved lead, and the residual liquid changes in composition and temperature along the line *a d*, until at *d* a point is reached at which it can hold no more lead in fluid solution. The result of this is that copper and lead separate isothermally from the solution, precisely as in the case of an eutectic. The copper separates in the solid state, but the lead remains liquid, retaining of course a certain small amount of copper in solution, and finally solidifies on the horizontal line *g h*. It will be noticed that the temperature of this final solidification is above that of the true copper-lead eutectic as given at *c*. This may arise from the fluid lead which separates at the temperature *f d*, retaining in the subsequent cooling, the copper which it contained at that temperature.

In cooling an alloy having a composition between *d* and *e*, it separates on meeting the curve *d* C *e* into two conjugate solutions, one rich in copper and the other rich in lead, which travel respectively down the limbs C *d* and C *e*, the change in composition of each being effected by a constant exchange between the solutions, one of these becoming richer in copper and the other richer in lead.

When the solution which is rich in copper reaches the temperature and composition *d*, the copper solidifies, and this is indicated by the horizontal line *d i*. The droop in this line between *i* and *e* is probably due to a condition of imperfect equilibrium between the two solutions when one becomes very small in amount.

As additional examples of binary alloys of this class may be mentioned the lead-zinc, bismuth-zinc, lead-aluminium, bismuth-aluminium and cadmium-aluminium series, which are not miscible in all proportions when fluid.

The solidification of ternary alloys which are not completely miscible when fluid introduces so many complications that it would hardly be worth while to devote any space to it in the present Paper; but the work of Alder Wright * will afford valuable material to aid in the solution of such a problem.

Molecular changes in solid metals and alloys.—In addition to the changes of state of matter—from the gas to the liquid, and from the liquid to the solid—there are other molecular changes which take place as the temperature is lowered and which produce more or less abrupt evolutions of heat. These changes which take place in the solid state are called allotropic changes in the case of elementary substances, and their study has proved during recent years a most fruitful branch of research. This is especially the case in metallurgical work, the hardening and annealing of steel, for instance, being entirely dependent on such changes.

When a metal changes from one allotropic form to another, its physical properties are found to undergo a sudden change. The most important of these changes is perhaps that in its power of dissolving other metals. In this respect an allotropic change is precisely analogous to the change from liquid to solid, and much that has been learnt about the nature of solidification may be applied directly to allotropic changes. This will be seen clearly in Fig. 190 (page 199), which represents the solidification and subsequent changes in a fused mixture of silver and sodium nitrates; † the upper part of the diagram was given in Fig. 184 (page 189). The part *d* C *e* of the critical curve has again been added, although it cannot be experimentally realised, in order to render more obvious the fact that the lines *g d* and E *e* are parts of the typical critical curve of miscibility for solids.

In the series under discussion silver nitrate is found in three distinct forms — liquid, rhombohedral, and rhombic, but sodium nitrate only exists as a liquid and in the rhombohedral form.

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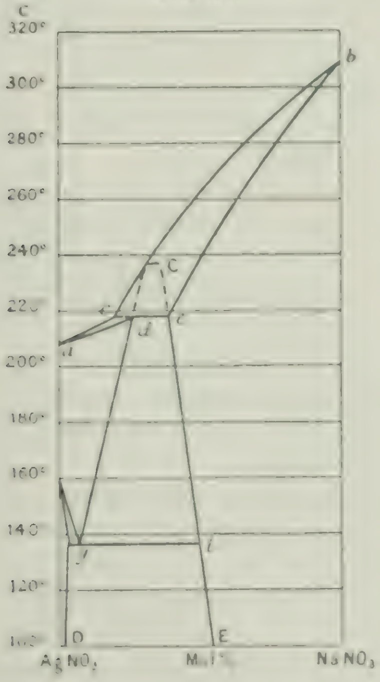
* Alder Wright, Proceedings, Royal Society, 1889–1894, vols. xlv, xlviii, xlix, l, lii, lv.

† Roozeboom, loc. cit.

During the progress of solidification there are obtained solid solutions containing from 0 per cent. to 26 per cent. $NaNO_3$, and from 38 per cent. to 100 per cent. $AgNO_3$. Both these series are rhombohedral. As the temperature falls still further, the compositions of the conjugate solutions become more widely separated, as indicated by the lines *d g e l*, and the latter line is continued down to the ordinary temperatures.

FIG. 190.



The critical solution indicated by *d g* undergoes a sudden change in composition at the point *g*, becoming suddenly less rich in $NaNO_3$, and changing to the rhombic crystalline form. This change in solubility accompanies the change of the solid solvent ($AgNO_3$) from the rhombohedral to the rhombic form. This occurs in the pure solvent at 160° C. (320° F.), but the temperature of change is progressively lowered by increasing the amount of $NaNO_3$, until at *g* the conjugate solution changes to the rhombic form at 138° C. (280·4° F.).

The change of crystalline form in the solid solution is analogous to the solidification of a liquid solution, and the lowering of the change point may be calculated if the amount of heat evolved during the change in the pure solvent is known, just as the lowering of the freezing point can be calculated from the latent heat of fusion. This was pointed out by one of the authors * in the case of steel. It must be remembered, however, that sufficient time must be allowed for the rhombic crystals which form to arrive at a state of equilibrium with the *whole* of the rhombohedral solution, and that as this is only arrived at as the result of the gradual diffusion of $NaNO_3$ in solid $AgNO_3$ at the comparatively low temperature of 140° C. (284° F.) it cannot be accomplished at all rapidly.

Molecular changes in solid steel.—In considering the molecular changes in solid metals and alloys the authors preferred first to discuss the mixtures of silver and sodium nitrate, although it does not really come under this heading, because it has been so fully worked out by Bakhuis Roozeboom, and because it is a comparatively simple case, and the knowledge gained in studying it will greatly facilitate the investigation of the more complicated molecular changes which take place in solid steel.

The changes in steel and in more highly carburised iron are in fact so complicated that want of space precluded an attempt to deal with them here, more especially as a Paper by Bakhuis Roozeboom, "Eisen und Stahl vom Standpunkte der Phasenlehre," † was going through the press when this Paper was written. Both of the authors ‡ have moreover treated the subject on various occasions, and from different points of view.

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* Stansfield, Journal, Iron and Steel Institute, 1899, II, page 169.

† Bakhuis-Roozeboom, Journal, Iron and Steel Institute, 1900, II, page 311.

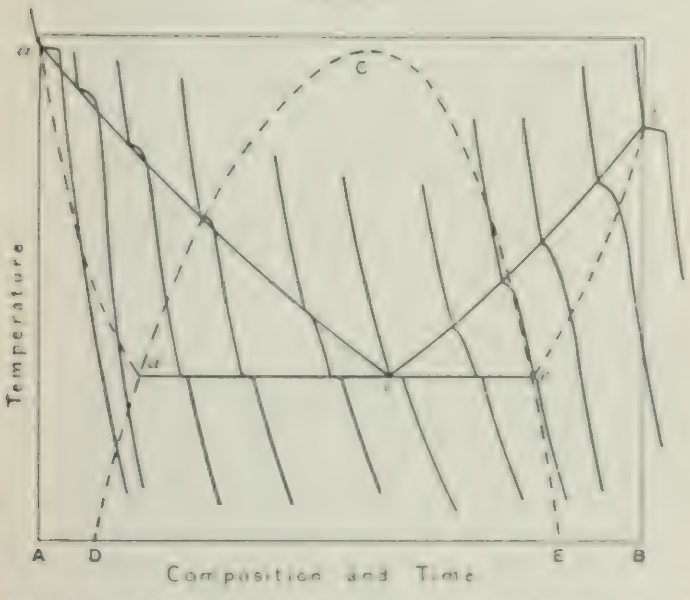
‡ Roberts-Austen, Proceedings, Institution of Mechanical Engineers, 1899, Stansfield, loc. cit., and Journal, Iron and Steel Institute, 1900, II, page 317.

ADDITIONAL NOTE. (October 1900.)

The authors have represented, in Fig. 191, the connection between the different kinds of curves that have been considered in this Paper. A number of cooling curves of different alloys of the two metals A and B have been placed side by side in such a way that their position in the diagram denotes approximately their composition.

The curves *a c* and *b c* passing through the points of initial solidification of the series are the curves of equilibrium between the solid and liquid states, and the horizontal line *d e* passing through the points of final solidification indicates the solidification of the eutectic alloy. The points *d* and *e*, which limit this line, mark the ends of the curves *a d* and *b e* which show the composition of the separated solid. The points *d* and *e* also lie on the critical curve DCE.

FIG. 191.



The portions *d*D *e*E of this curve can alone be realised, and their positions can be determined by measuring the amount of the one metal that can be dissolved by the other metal at each temperature. In other words, these curves indicate the compositions of the richest alloys that can be produced by the diffusion of one metal into the other in the solid state.

The co-ordinates employed in the figure are time and temperature in the case of the cooling curves, and composition and temperature in the case of the critical curve and the curves of equilibrium. By giving a double meaning to the abscissae the use of three co-ordinates was avoided.

The Appendix is illustrated by Figs. 175 to 191 in the letterpress.

APPENDIX II. TO SIXTH REPORT TO THE ALLOYS RESEARCH COMMITTEE.

MALLEABLE IRON CASTINGS.*

By Mr. C. O. BANNISTER, Assoc. Royal School of Mines.

For the cheap manufacture of iron articles requiring a fair amount of strength, it has been found convenient to first cast them and then to partially decarburise the castings by an oxidizing cementation treatment, thus producing a coating of malleable iron over a core of brittle cast-iron. The articles thus made are known as malleable iron castings, malleable iron or run steel. This process is specially useful for small articles of intricate shapes. Fairly large articles, such as propeller shafts, etc., have been made by this process and a subsequent operation for case-hardening.

Although this process was described by Reaumur in 1722, patents were only taken out in 1804 by Lucas and in 1850 by Brown and Lennox.

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* Part of a Thesis presented for the Honours Associateship of the Royal School of Mines. This Thesis was handed in by Sir William Roberts-Austen in October 1901.

As modifications of the process, mention may be made of the method proposed in 1828 by Karsten, which was to submit iron castings to a glowing heat in a current of air; and of Tunner's method, proposed in 1846, which was to expose iron castings to a red heat in boxes filled with sand and allowing a regular admission of air; the action in this last method was sometimes aided by the use of substances which provided oxygen, such as haematite, hammer scale, etc. Briefly, the process, as generally practised, consists of heating the castings packed in haematite to a bright red heat for several days.

The castings of the best Cumberland white or grey iron are made in sand moulds with or without chills, and packed with haematite in iron boxes. The haematite is crushed and passed through a 70- or 80-mesh sieve and mixed with used haematite from a previous operation, because the fresh haematite alone is too vigorous in its action. The mixture generally used consists of two-thirds used and one-third fresh, sometimes a mixture of half and half is used. Used haematite is sometimes reoxidised by the addition of a little sal-ammoniac and spreading it out in the open air.

The boxes, cast from a special mixture of white iron and scrap, vary in size, according to the size of the castings to be annealed, and may have a circular or rectangular horizontal section.

The furnaces consist of rectangular chambers, with dome-shaped roofs, built in rows, each communicating with a flue which leads to a stack. The furnaces may be coal or gas-fired; the sketch, Fig. 192, Plate 44, represents a coal-fired furnace, such as is generally used in the Midlands. The middle portion of the bed is raised, thus providing two passages down the sides for the fires. The boxes containing the castings are placed on this raised floor, three or four in each pile, the joints between them being sealed with fire-clay or wheel swarf, and the top box is completely covered with the same substance. Each furnace holds from twelve to twenty boxes. After the fires have been started, a bright red heat (between 1,000° C. or 1,832° F. and 1,100° C. or 2,012° F.) is maintained during the day; at night the ovens are damped down and only a dull red heat obtained, until the fires are again made up in the morning. This heating goes on for several days, from five to nine according to the size of the castings and the degree of decarburization desired; after the furnaces have been allowed to cool for one or two days, the boxes are withdrawn and unpacked. The middle boxes of each row are found to work most evenly, and the most important work is always packed in these.

The great objection, which prevents this process from being much more extensively used, is the presence of small quantities of slag and blow-holes in the castings, which greatly reduce their strength, introducing an element of unreliability.

Much experimental work has been done in order to investigate the changes which take place in the composition of the iron during this process, the increase of strength, the most suitable cement, and the correct time of cementation.

The most important conclusions arrived at are:—

1. A malleable casting always contains amorphous carbon.
2. A casting may lose carbon and still remain fragile if the remaining carbon is not in the form of graphite, or if the initial quantity of graphite is not increased.
3. A casting may become malleable without a sensible loss of part of its total carbon.
4. In general practice the castings lose on the total carbon, and some of the combined carbon is converted into finely-divided graphite or temper carbon.
5. The castings generally lose some sulphur, which is found in the haematite in such a form as to evolve sulphuretted hydrogen on treatment with acids.
6. As a rule the other constituents of the castings are not altered to any appreciable amount.

The following work has been done to show by means of analyses and photo-micrographs the changes which take place during the operation. The preparation of the samples was left in the hands of a practical man, so the results are such as would be obtained in commercial objects.

Fig. 193, Plate 44, is a photograph of a cross section of the original bar highly polished, etched and magnified about three times. The analysis of this gave the following figures:—

Combined carbon	2·53 per cent.
Graphitic carbon	Nil.
Sulphur	0·36 ,, ,,
Phosphorus	0·036 ,, ,,
Silicon	0·707 ,, ,,
Manganese	0·185 ,, ,,

Fig. 194, Plate 44, is a photo-micrograph of the same iron magnified 1,600 diameters, and shows cementite and confused pearlite or sorbite. Sorbite is practically pearlite in which the laminae have not separated, and cementite is carbide of iron.

Fig. 195, Plate 44, is a photograph of a cross section of the bar after being annealed in haematite, polished, etched and magnified about three times. This shows how the decarburization has taken place from the outside, with the formation of graphitic carbon towards the centre. The analysis from the whole of a drilling through the bar gave :—

Combined carbon	0·74 per cent.
Graphitic carbon	1·33 ,, ,,
Sulphur	0·33 ,, ,,
Phosphorus	0·04 ,, ,,
Silicon	0·667 ,, ,,
Manganese	0·192 ,, ,,
Total carbon	2·07 ,, ,,

On comparing these figures with those given before, we find that the total carbon has been reduced from 2·53 per cent. to 2·07 per cent., that 1·33 per cent. carbon originally in the combined state has been converted into the graphitic condition, that the sulphur has been reduced by 0·03 per cent., and that the other constituents have only slightly varied.

The next set of photographs, Figs. 196 to 208, Plates 44 to 46, are a series taken from the outside to the centre of the annealed bar magnified 1,600 times, showing the gradual change in the iron. The graphitic carbon is so finely divided that, even at this magnification, it is difficult to detect.

Theory of the Process.—The temperature of the annealing furnace is carefully kept somewhere between 1,000° C. (1,832° F.) and 1,100° C. (2,012° F.), and it is a well-known and fully accepted fact that at a temperature of 1,050° C. (1,922° F.) cementite (Fe_3C) is dissociated into its constituent elements and produces a solid solution of free carbon in iron. Dr. Stansfield * has shown that when cast-iron is heated and allowed to cool slowly the carbon separates out as graphite, being less soluble in this form than when present in the form of cementite. At the annealing temperature, the cementite is dissociated and the graphite is left in a very finely divided condition. The reason the graphite does not crystallise is probably because: firstly, there is a certain mechanical opposition in the mass, caused by the separation of the graphite which occupies more space in this condition than it does when in solution; secondly, there was no crystalline graphite originally present in the bar which would have formed nuclei around which more graphite could collect.

On referring to the diagram, Fig. 209, Plate 47, showing the distribution of carbon in the annealed bar, it is found that after a certain point 0·5 per cent. carbon is reached, although the graphite increases from this point to the centre of the bar by 1 per cent., the combined carbon only increases by 0·3 per cent. The reason the amount of combined carbon is less near the surface of the bar is because the mechanical opposition to its dissociation is not so great, and therefore allows of the separation of the graphite to a greater extent.

During the decarburization of the bars there are two opposite actions continually at work. On the one hand there is the oxidising action of the cement (in this case haematite) on the outside of the bars, oxidising the carbon by solid contact, and also by gaseous diffusion according to the equations:—

$$2\,Fe_2O_3 + 3\,C = 4\,Fe + 3\,CO_2$$
$$CO_2 + C = 2\,CO.$$
$$Fe_2O_3 + 3\,CO = 2\,Fe + 3\,CO_2$$

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* Journal Iron and Steel Institute, II. [illegible] page 317

thus producing iron free from carbon (ferrite). On the other hand there is a store of carbon towards the centre of the bar in the form of non-crystalline graphite, which is continually recarburizing this ferrite by solid diffusion. These actions continue as long as a temperature of 1,050° C. (1,922° F.) is maintained, but on lowering the temperature they cease and the final product is as shown in Fig. 194, Plate 44.

The Appendix is illustrated by Plates 44 to 47.

APPENDIX III. TO SIXTH REPORT TO THE ALLOYS RESEARCH COMMITTEE.*

THE ALLOYS OF TIN AND ANTIMONY.

By Dr. W. REINDERS, of Breda, Holland.

The microscopic structure of the tin-antimony alloys has already been studied by Messrs. Charpy † and Stead,‡ but a complete freezing-point curve of these alloys has not been obtained. The one determined by Mr. Roland Gosselin shows three branches each having a concavity upwards, which is theoretically impossible, whilst Messrs. Heycock and Neville have only studied the first part of the curve, that is, alloy containing 0 to 5 per cent. of antimony. The author of this Appendix has determined their freezing-point curve, and has repeated the researches of Messrs. Charpy and Stead because these were not in accordance with the results of the melting-point curve. The freezing and recalescent points were determined by the method of Sir William Roberts-Austen, using as fixed points for the temperature scale melting tin, melting zinc, boiling sulphur, and melting aluminium, the rate of cooling being so arranged that the temperature fell from 450° C. (842° F.) to 150° C. (302° F.) in one hour. The materials used for the series of alloys were grain tin and star antimony and later chemically pure antimony reduced from tartar emetic. In all cases about 70 or 80 grammes were used.

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* This essay was handed in by Sir William Roberts-Austen in October 1901.

† "The Metallographist" Vol. I. 137, 1898.

‡ "The Metallographist" Vol. II. No. 4; Journal Society of Chemical Industry, December 1898.

The results obtained are given in the following Table 32.

TABLE 32.

Percentage of Antimony.	Freezing point.	Recalescent points.		
	C.°	C.°	C.°	C.°
100	622	—	—	—
95	612	—	—	—
90	600	439	—	—
85	583	428	—	—
80	564	428	—	—
80	566	433	—	—
70	527	427	—	—
60	484	425	308	237
55	457	428	308	230
52	430	—	—	238
51	435	—	—	246
50	427	—	312	240
50	433	—	307	239
50	425	—	309	240
45	415	—	315	242
40	395	—	306	240
30	358	—	305	243
20	311	—	—	242
10	256	—	—	242
0	232	—	—	—

Fig. 210, Plate 48, gives the freezing-point curve. It consists of four branches. The first, AC, begins with pure tin, melting at 232° C. (449·6° F.), and ends in C at 243° (469·40° F.) with 8 per cent of antimony.* A eutectic point, lower than the melting point of tin, does not exist. The smallest addition of antimony to tin raises the melting point. The crystals which separate along this curve are not pure tin, but an isomorphous mixture of tin and antimony. The constitution of these crystals, indicated by the points on the curve A F, will vary with the constitution of the fluid from which they crystallised, and will at the same time contain more antimony than the liquid does. According to a determination of Mr. van Bijlert † a fluid containing 4·63 per cent. of antimony gives crystals containing 6·3 per cent. Assuming that the difference in concentration between the fluid and the crystals is proportional to the percentage of antimony, those with the highest possible percentage of antimony (F) which crystallise at C would contain 11 per cent. of antimony.

At C begins the second branch C D, which is considerably steeper than the first. The crystals which separate along this branch are a chemical compound of tin and antimony. They are beautifully formed cubes and can be seen very well in the polished surface of an alloy containing 10 per cent. of antimony. They are lighter than the fluid from which they separate, so that they accumulate at the upper part of the solidified metal. On etching this surface with dilute nitric acid, these crystals appear as little glittering squares embedded in a dark field, as shown in Fig. 212, Plate 49. This dark field has the same appearance and structure as pure tin when treated in the same manner. It consists of the tin-antimony mixed crystals, which were formed when the fluid reached the point C. The glittering cubes have been isolated by Stead ‡ out of an alloy with 10 to 30 per cent. of antimony. He has made an analysis of them, and found they contain 51·44 per cent. of antimony, and he therefore assigned to them the formula Sn Sb (theoretically 50·5 per cent. of antimony); Behrens * has also isolated these cubes. His analysis, however, gave 33·7 per cent. of antimony, which corresponds with the formula Sn_2 Sb. It is a difficult matter to decide which is the true value, as the errors in the method of isolation are probably large enough to account for such differences of analysis.†

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* The beginning of this curve has been carefully determined by Messrs. Heycock and Neville. Journal, Chemical Society, [illegible] 1890), page 387.

† Zeitschrift fur Physik. Chem., 8, 357.

‡ "The Metallographist," Vol. II, No. 4.

When the alloys contain more than 20 per cent. of antimony, the cooling curves show three retardations during cooling.

The first and the third are always well marked, but the second is very feeble, and occurs at a temperature of 309° C. and gives the point D, Fig. 210, Plate 48, where the third branch D E begins. The percentage of antimony is here about 20. The crystals which separate along the branch D E could not be well discerned in the sections of alloys with 30 and 40 per cent. of antimony. The cross section contained a number of crystals which were generally larger than those in the lower alloys, whilst here and there they were arranged in trains which intersected in an acute angle; in most cases the cubes of the curve D C could be well discerned.

In the 50 per cent. alloy the crystals have again a definite form. They are, as Stead says, thick plates which fill almost the whole section. Between them is the black mass consisting of an isomorphous mixture of tin with antimony. Cubes are totally absent. The general toughness of tin is gradually lost by adding antimony to the alloys with more than 10 per cent. antimony, and the 50 per cent. alloy is brittle and much harder than tin. The maximum point of the curve D E, indicating the constitution of the compound which crystallises in plates, lies above the point E, where the third and fourth branches intersect at 430° C. (806° F.) and 51 per cent. antimony. The plates contain therefore more than 51 per cent. antimony and correspond probably to Sn_4 Sb_5 (55·6 per cent. Sb).

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* Verslagen Kon. Acad. v. Wetenschappen te Amsterdam, 25 Juni, 1898, page 58.

† In the meantime, Mr. van Eijk (Proc. Kon. Akad. Wetenschappen te Amsterdam, 1902, 859) has succeeded, by centrifuging at 270° C., in nearly separating the whole of the crystals from the fluid. His analysis gave 32·5 per cent. of antimony.

The curve E B ends in B, the freezing point of pure antimony. Probably the crystals which freeze along this curve are not pure antimony, but contain some tin in solid solution, the percentage of which varies with the constitution of the liquid.

An alloy of 60 per cent. antimony shows four retardation points, the first at 484° C. (903·2° F.) and especially the second one at 430° C. (806° F.) are well marked, the third and fourth at 310° C. (590° F.) and 243° C. (469·4° F.) respectively are very feeble. In the section of this alloy three different bodies may be seen. First, long needles with rounded edges; they are a little browned by etching with dilute nitric acid, and project most from the field. The space between them is occupied by the thick plates of the 50 per cent. alloy, which are separated by thin black lines of the tin crystals. The rounded edges of the long needles, which will be the antimony crystals, show that they are inclined to dissolve when the point E is reached and the thick plates can be formed; just as a salt hydrate with less water dissolves again when a transition point is reached, so that the solution from which it has separated at a higher temperature can deposit a hydrate with more water.

This transformation of the fluid E with the antimony crystals J into the compound M ought to take place at the constant temperature of 430° C. (806° F.), till either the fluid or the crystals J had totally vanished. In the case of the 60 per cent. alloy the fluid E ought to disappear, so that the solidified mass would consist of a mixture of the crystals N and crystals of the antimony type. The fact that between the thick plates of the compound N the black lines of the tin crystals were visible, and that the cooling curve shows the points D and C proves that the transformation at 430° C. (806° F.) was not total. The rate of cooling was too fast; only by very slow cooling would the real equilibrium have been reached.

In alloys containing more than 60 per cent. of Sb. the points D and C disappear in the cooling curves. In the polished sections the long needles grow longer, and more and more resemble the dendritic crystals of pure antimony. It was very difficult to obtain a good section of these alloys, because the metal is very brittle, and, on polishing, the crystals of the antimony type fall out of the surface.

Crystals other than those described were, however, not observed, nor did the freezing-point curve give any indication of such, so that the following conclusion is reached :—

Tin and antimony can form two isomorphous mixtures, one of the tin type, containing a maximum of 11 per cent. antimony; another of the antimony type, containing an unknown quantity of tin.

Furthermore, they form two compounds, one crystallising in little cubes, which have the constitution $Sn_2 Sb$; another, appearing in thick plates, having probably the formula $Sn_4 Sb_5$.

The Appendix is illustrated by Plates 48 and 49.

A further Appendix on "The Effect of Strain and Annealing," by Dr. William Campbell, was selected by the Council to be read at the Joint Meeting with the American Society of Mechanical Engineers in Chicago, and will be published in Part 3 of the Proceedings 1904.

Fig. 4. *Rough Polishing Apparatus used for polishing specimens.*

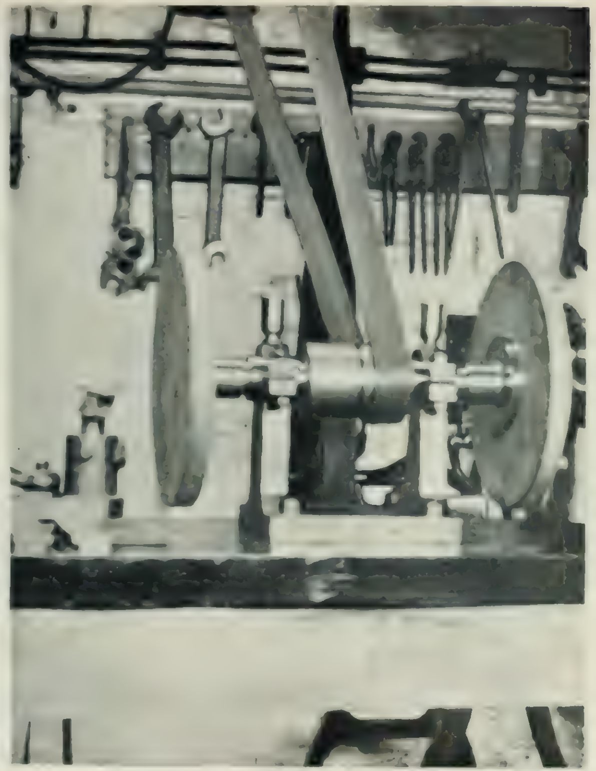


Fig. 5. *Fine Polishing Apparatus used for final polishing.* Plate 1

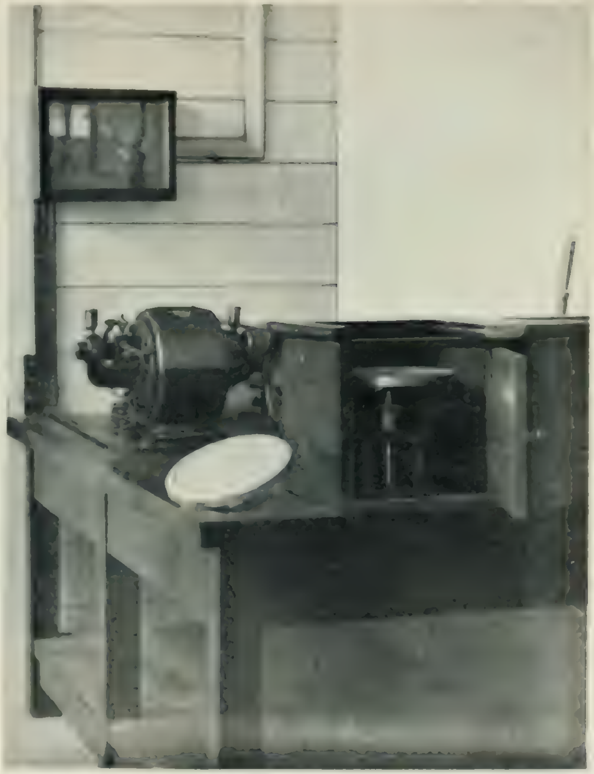
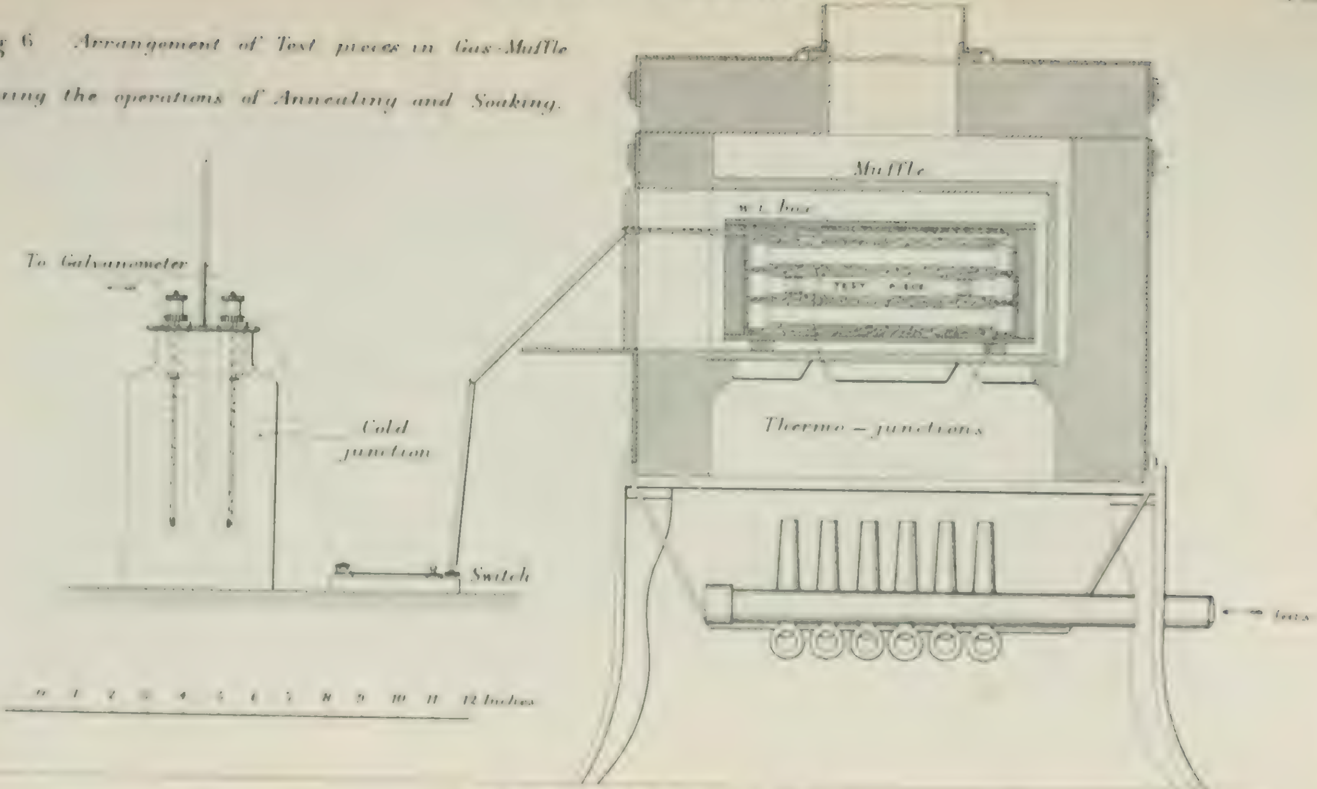


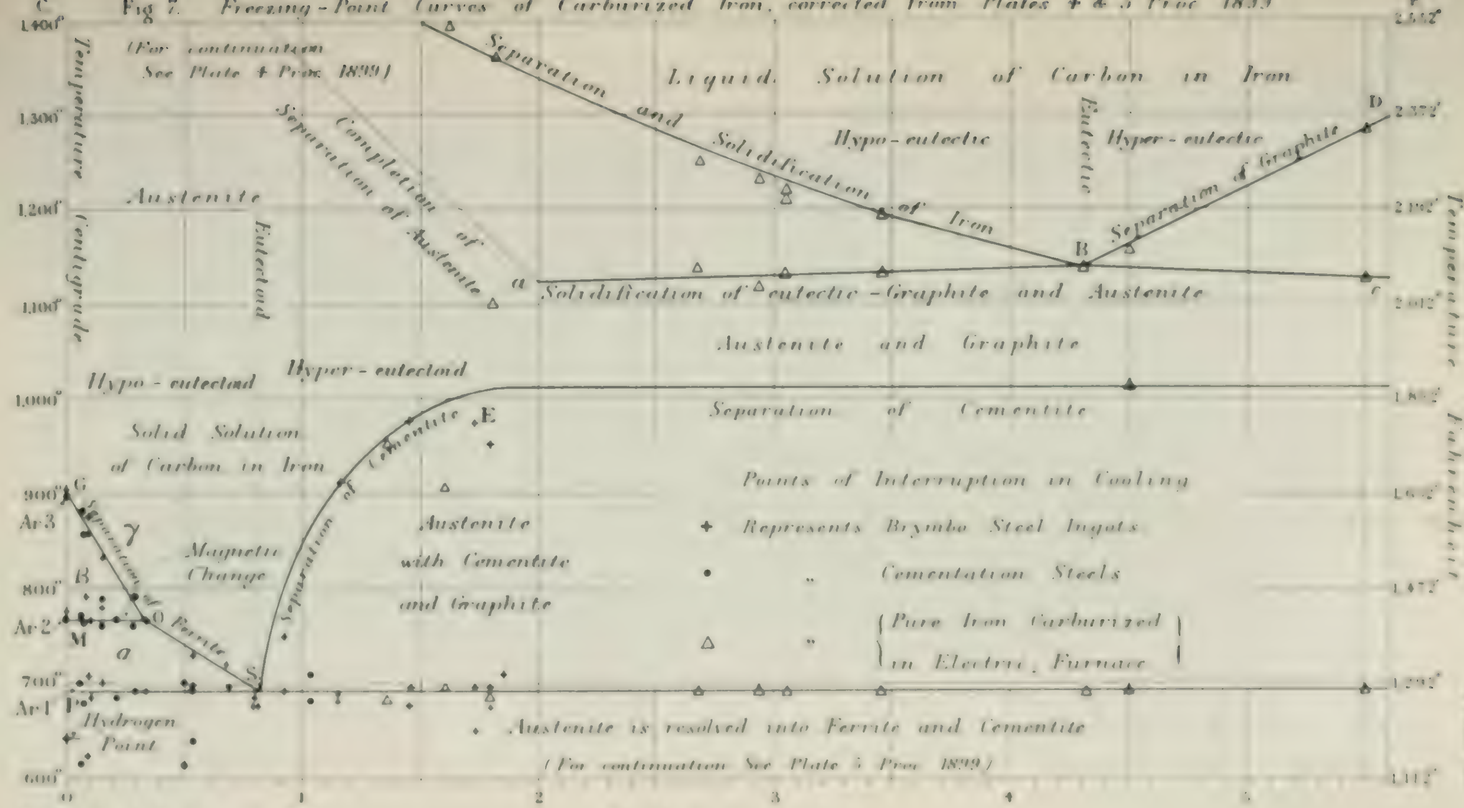
Fig 6. Arrangement of Test pieces in Gas-Muffle during the operations of Annealing and Soaking.



ALLOYS RESEARCH

Plate 3

Fig 7. Freezing-Point Curves of Carburized Iron, corrected from Plates 4 & 5 Proc 1899



Mechanical Engineers 1904

Fig 8. *Steels as received (Rolled)*

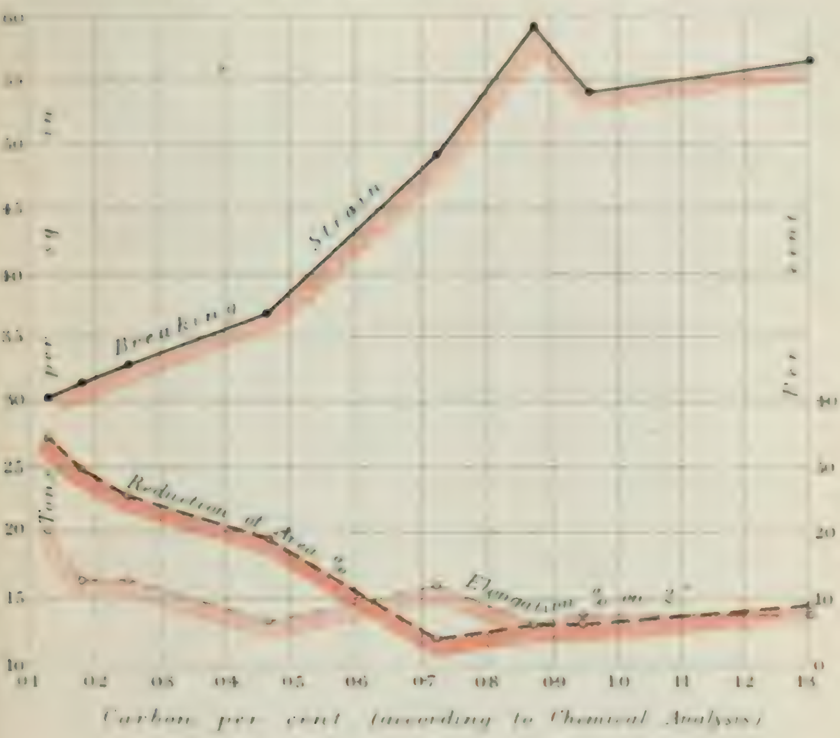
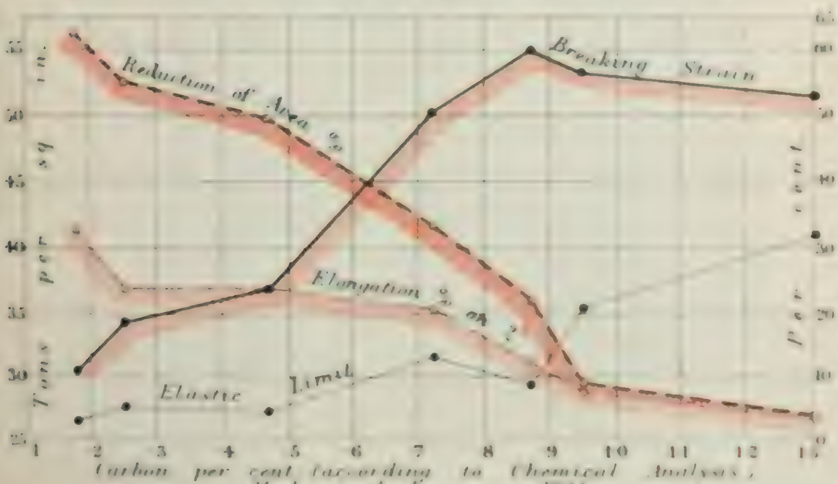


Fig 9. *Steels annealed at 620° C (1,148° F.) for ½ hour*



Mechanical Engineers 1904

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Plate 5

Fig 10 *Steels annealed at 720° C (1328°F) for ½ hour*

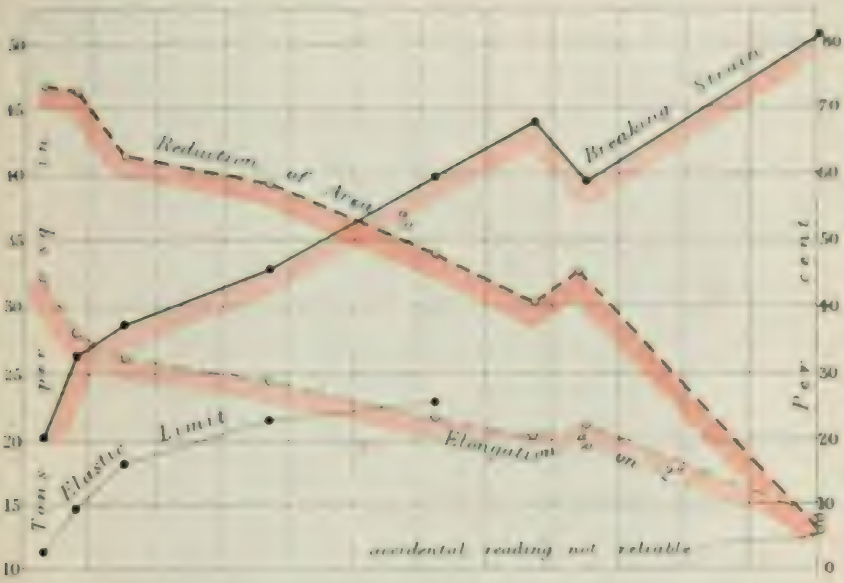
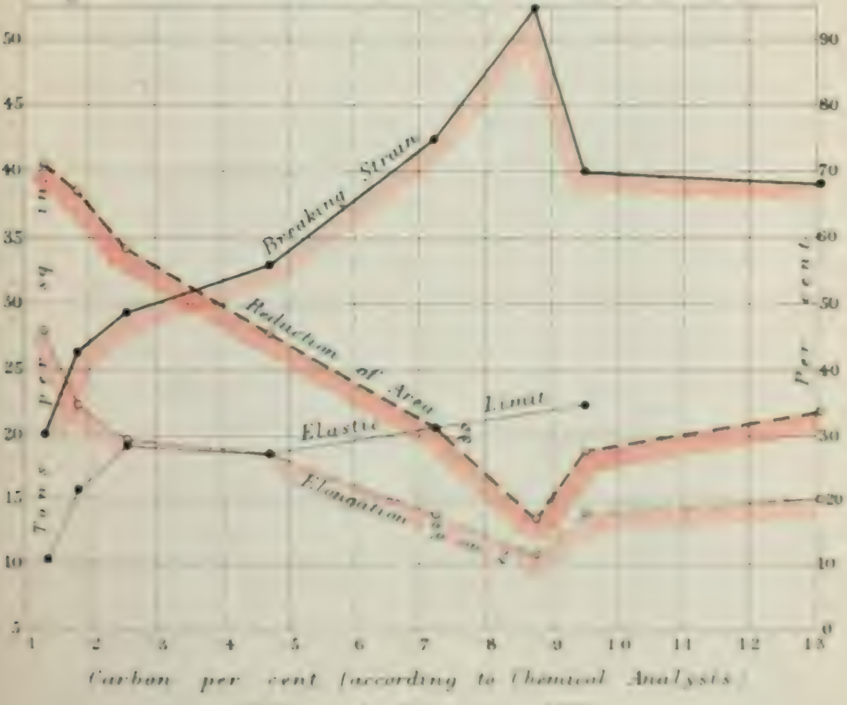


Fig 11 *Steels annealed at 800° C (1472°F) for ½ hour*



Mechanical Engineers, 1904

Fig 12. *Steels annealed at 900° C (1,652° F) for ½ hour*

N.B. *Extension and Reduction of Area become marked at 675° C*

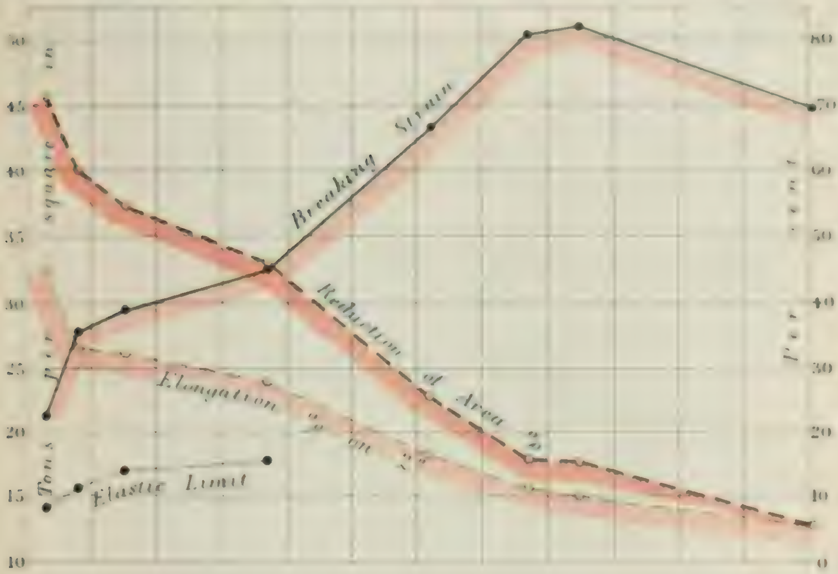


Fig 13. *Steels annealed at 1100° C (2,012° F) for ½ hour*

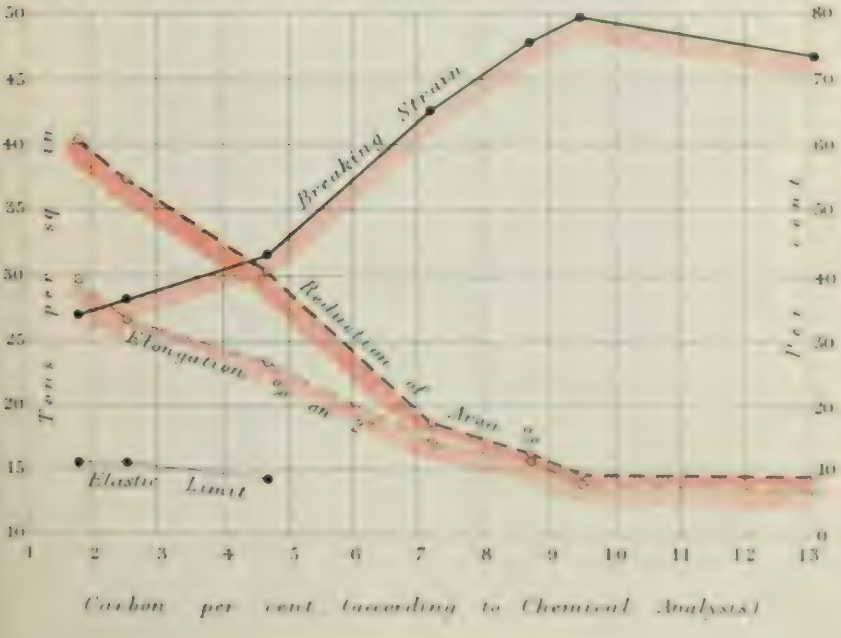


Fig 14. Steels soaked at 620° C (1,148° F) for 12 hours

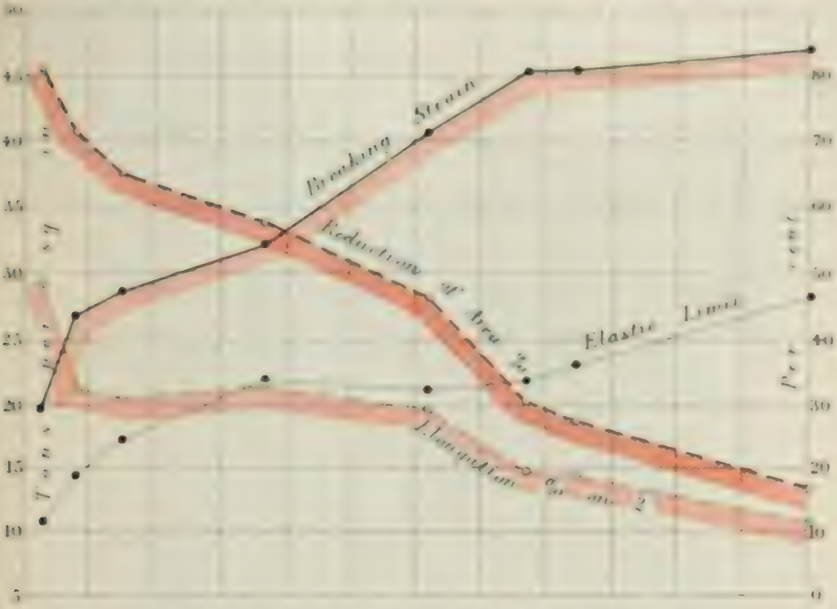


Fig 15. Steels soaked at 720° C (1,328° F) for 12 hours

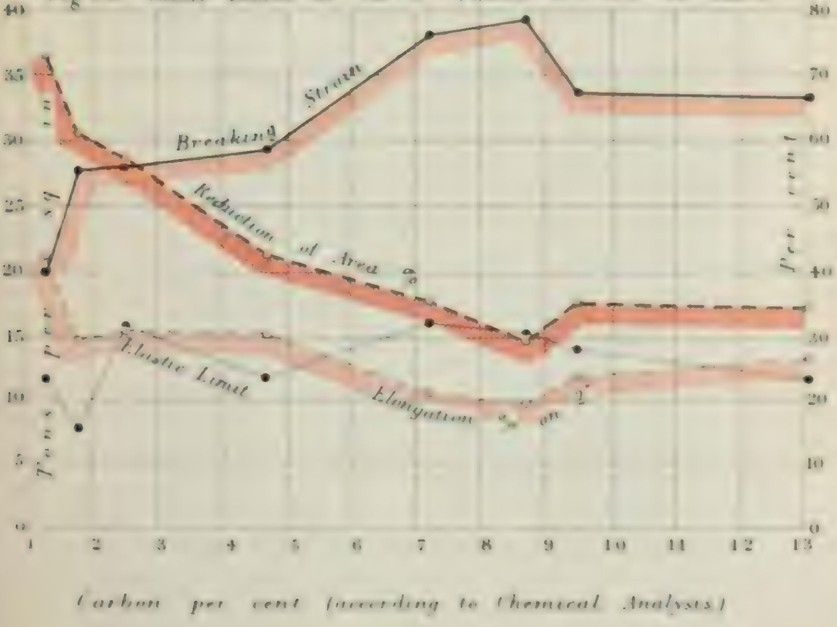
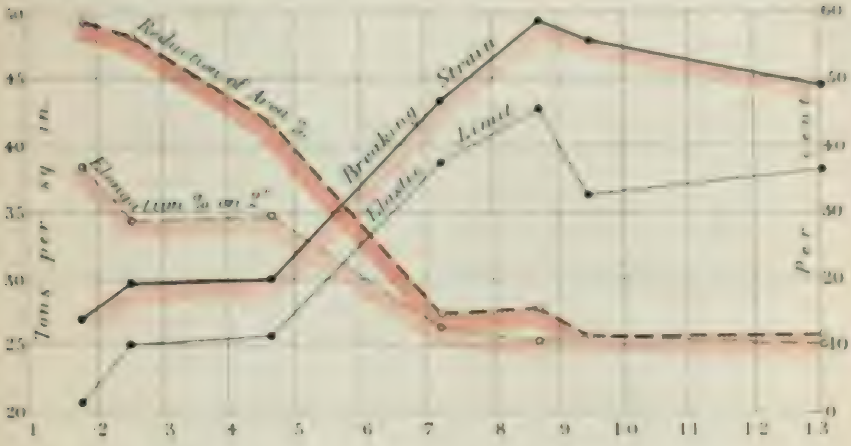


Fig 16.

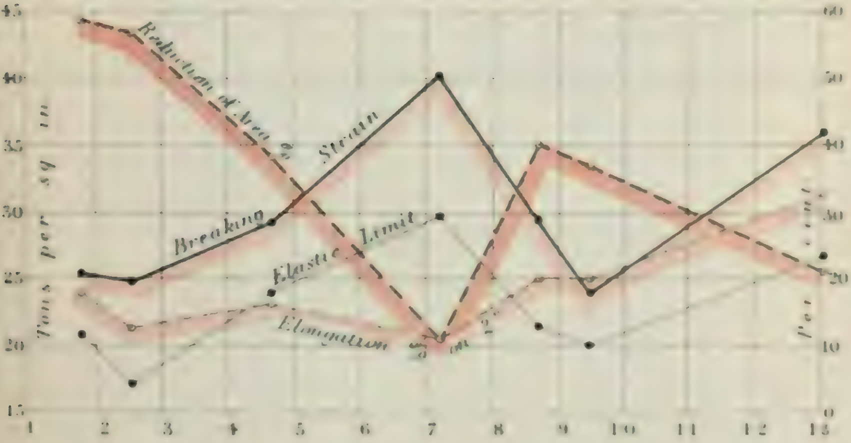
Steels soaked at 900° C (1,652° F) for 12 hours



Carbon per cent (according to Chemical Analysis)

Fig 17

Steels soaked at 1,200° C (2,192° F) for 12 hours



Carbon per cent (according to Chemical Analysis)

Fig 18. *Steels quenched at 720° C (1,328° F) in Water*

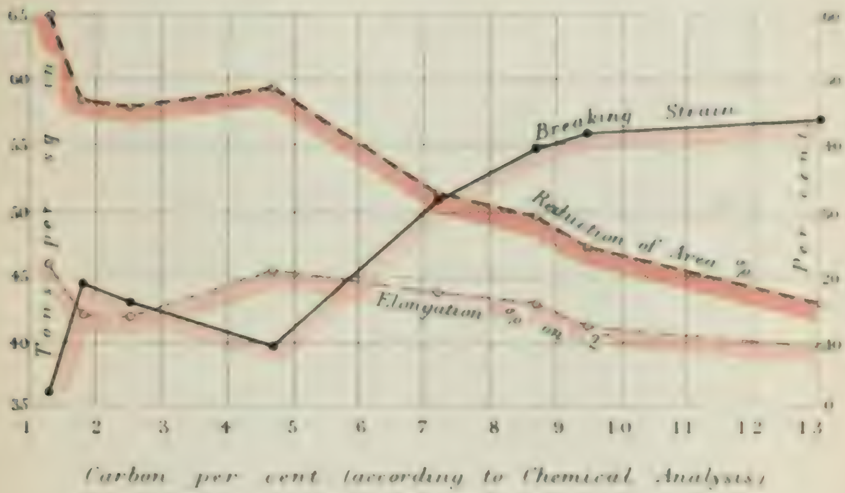
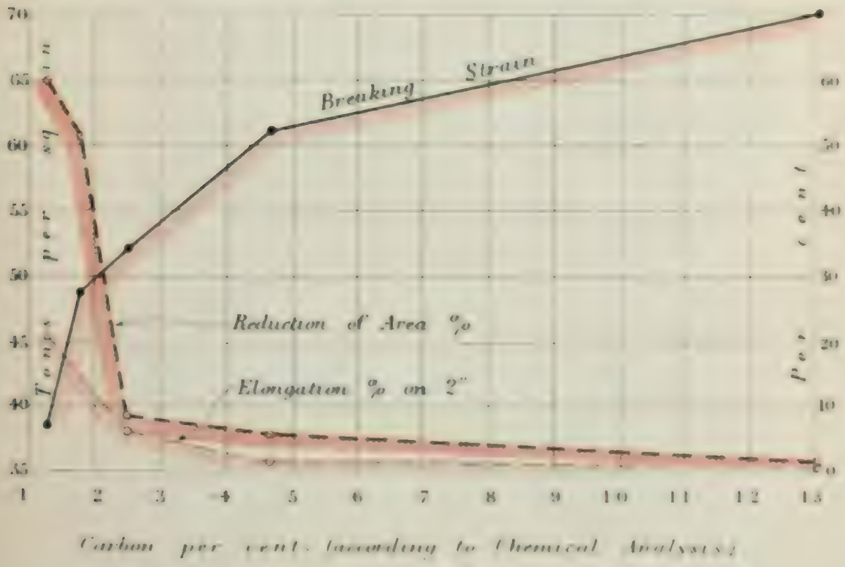


Fig 19. *Steels quenched at 800° C. (1,472° F) in Water*

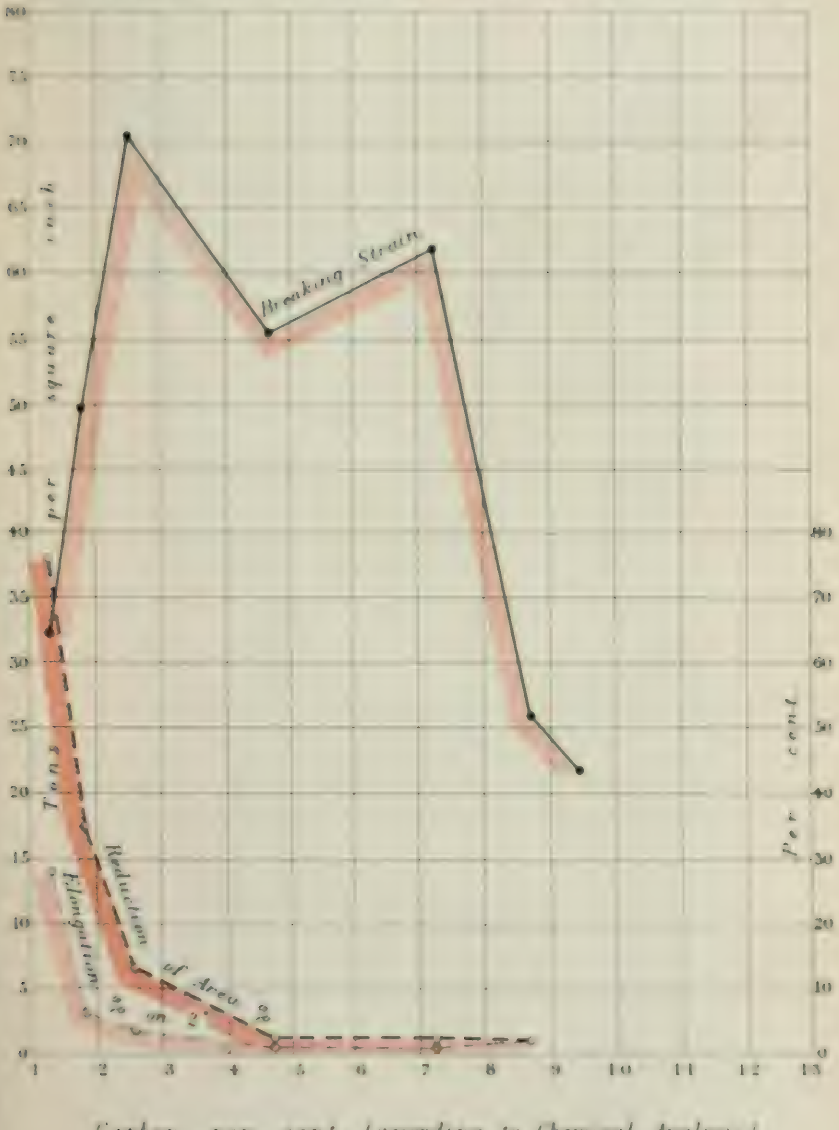


ALLOYS RESEARCH

Plate 10

Fig 20

Steels quenched at 900° C. (1,652° F.) in Water



Mechanical Engineers 1904

Fig 21

Steels quenched at 1200° C (2192° F.) in Water

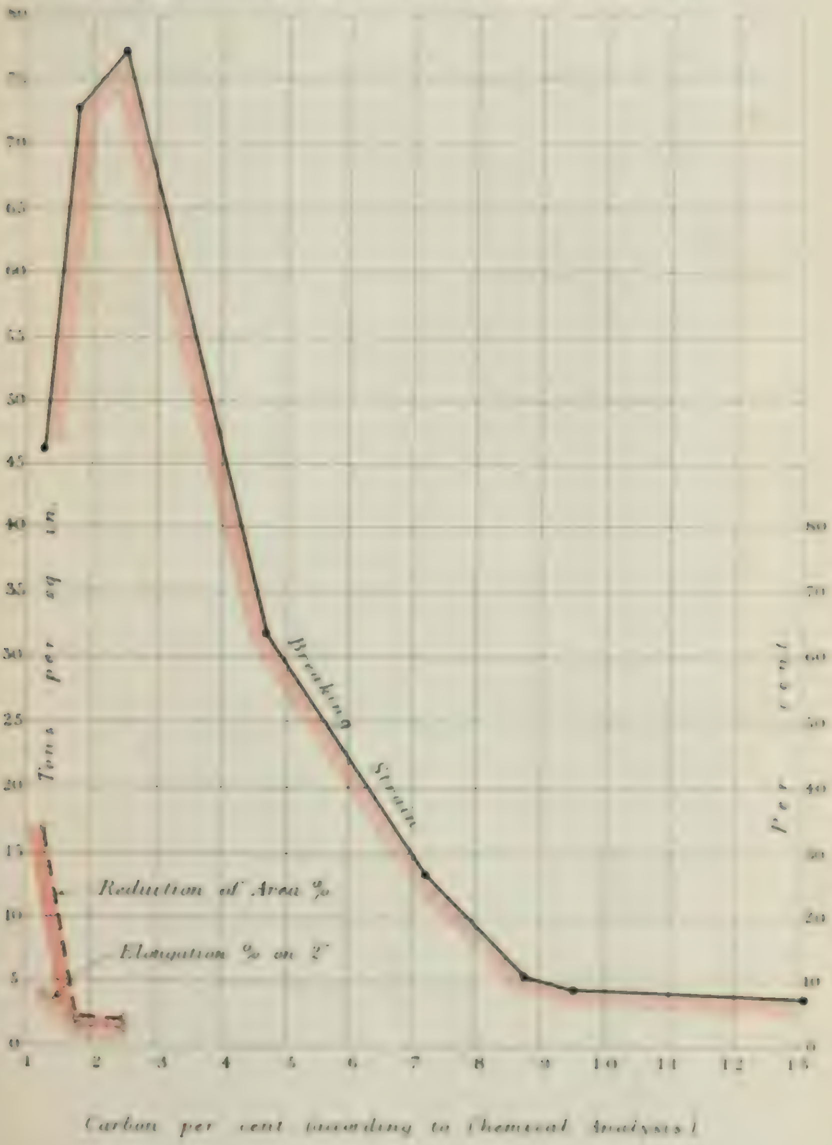


Fig 22.

Steels quenched from 720°C (1328°F) in Oil.

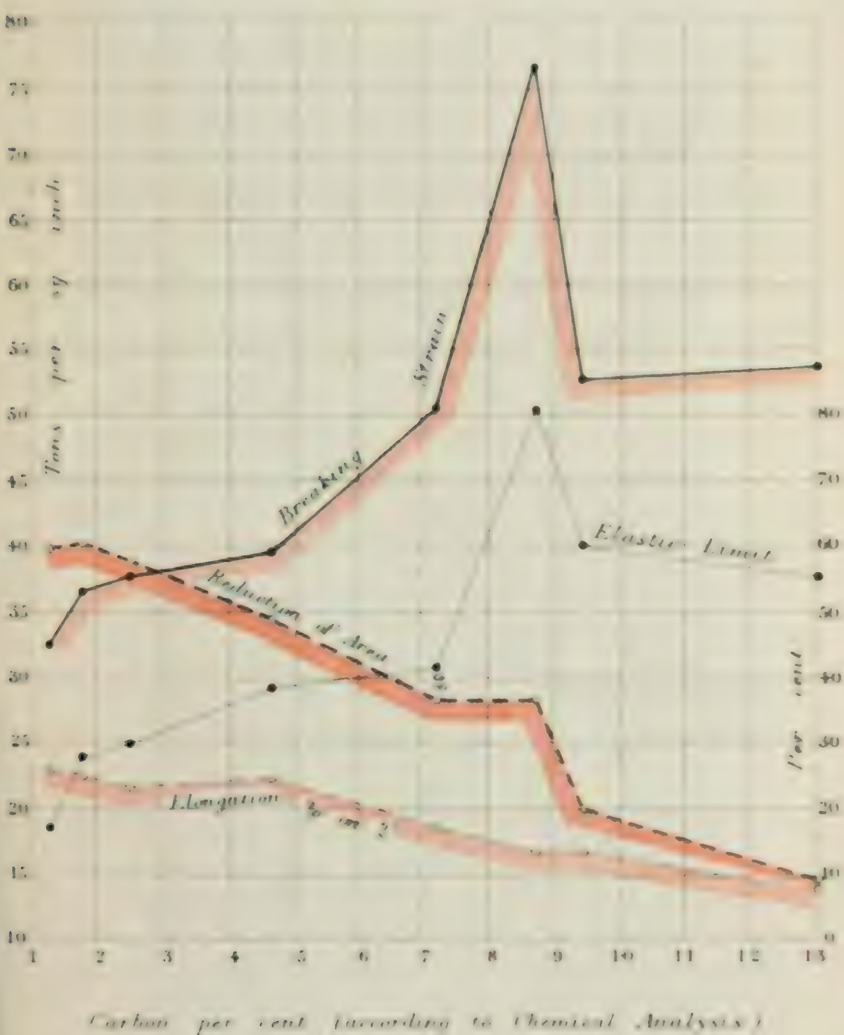
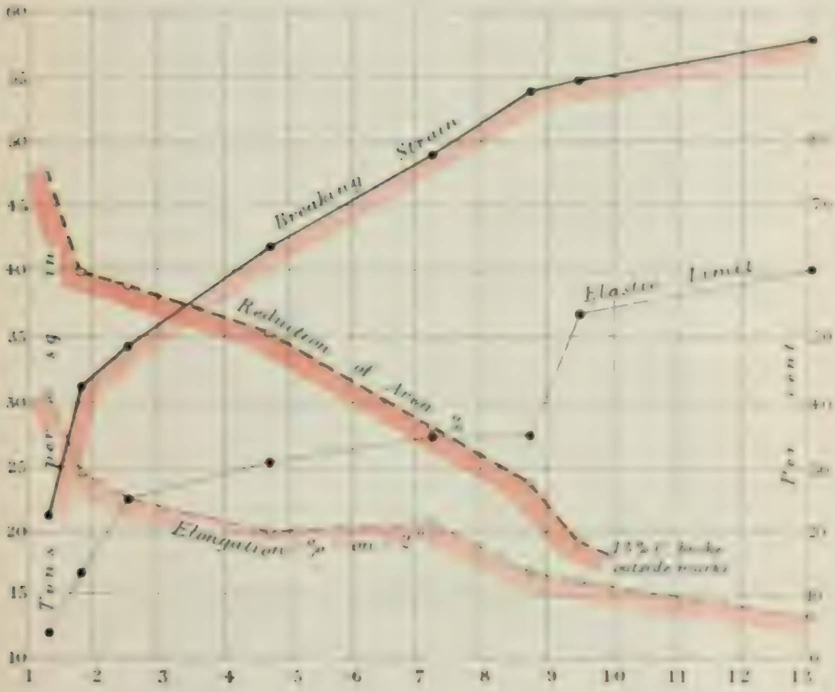


Fig. 23

Steels quenched from 720° C (1328° F) in Oil

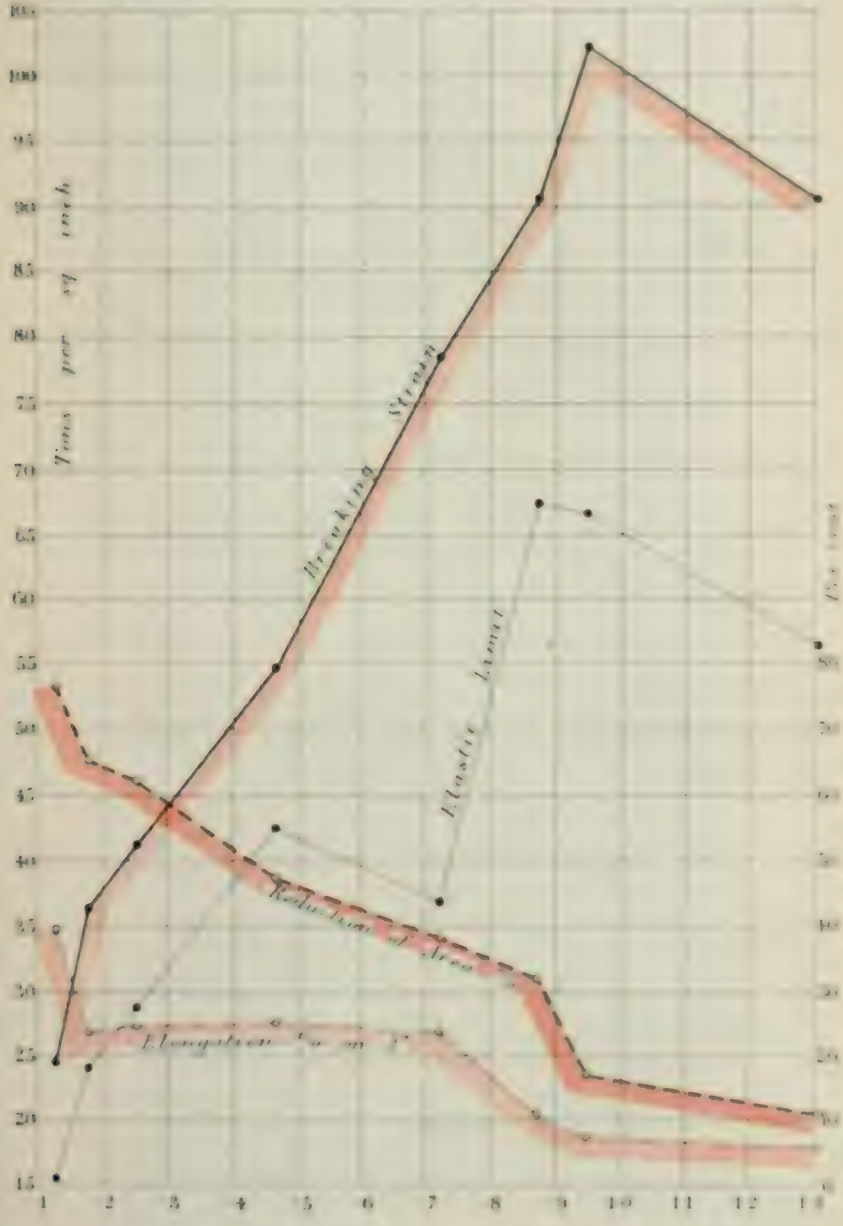
and Reheated to 350° C (662° F)



Carbon per cent (according to Chemical Analysis)

Fig 24

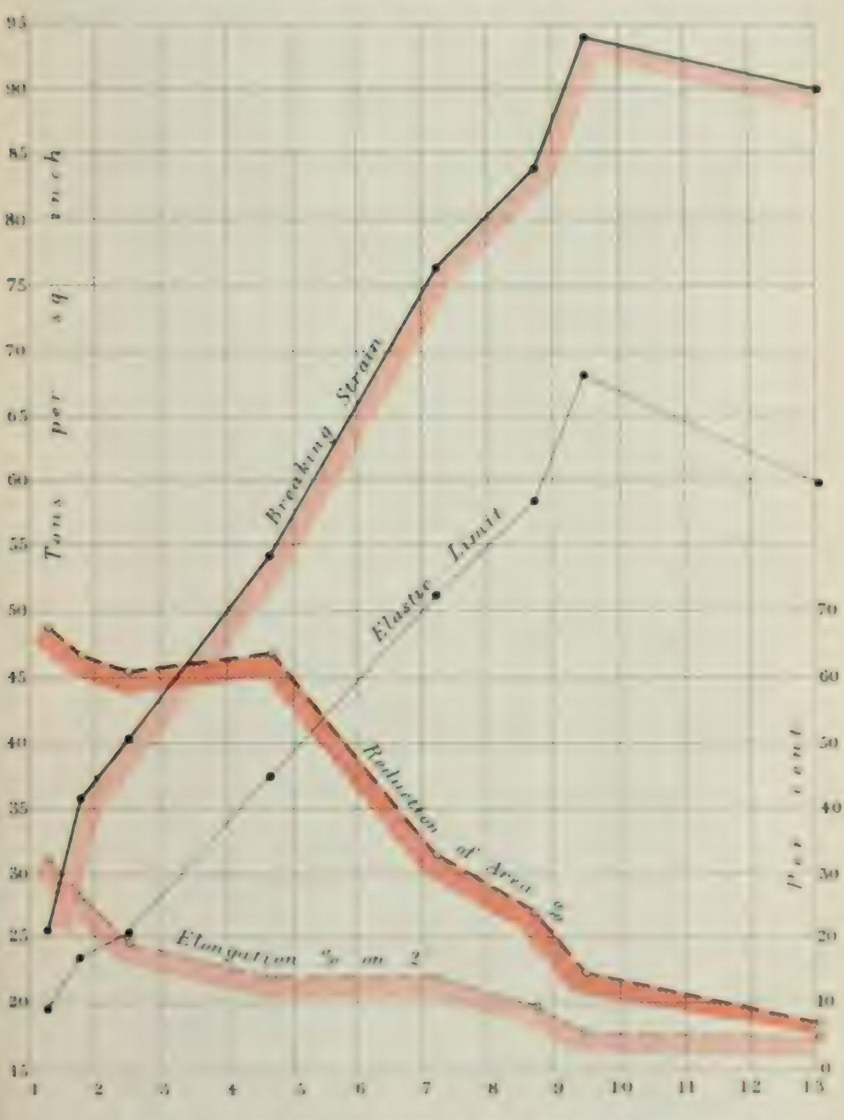
Steels quenched from 870°C (1598°F) in Oil, and Reheated to 550°C (1022°F)



Carbon per cent (according to Chemical Analysis)

Fig 25

Steels quenched from 1,000° C (1,832° F) in Oil, and Reheated to 350° C (662° F)



Carbon per cent (according to Chemical Analysis)

Mechanical Engineers 1904

Fig 26 *Steels quenched from 800° C (1,472° F) in Oil, and Reheated to 600° C (1,112° F)*

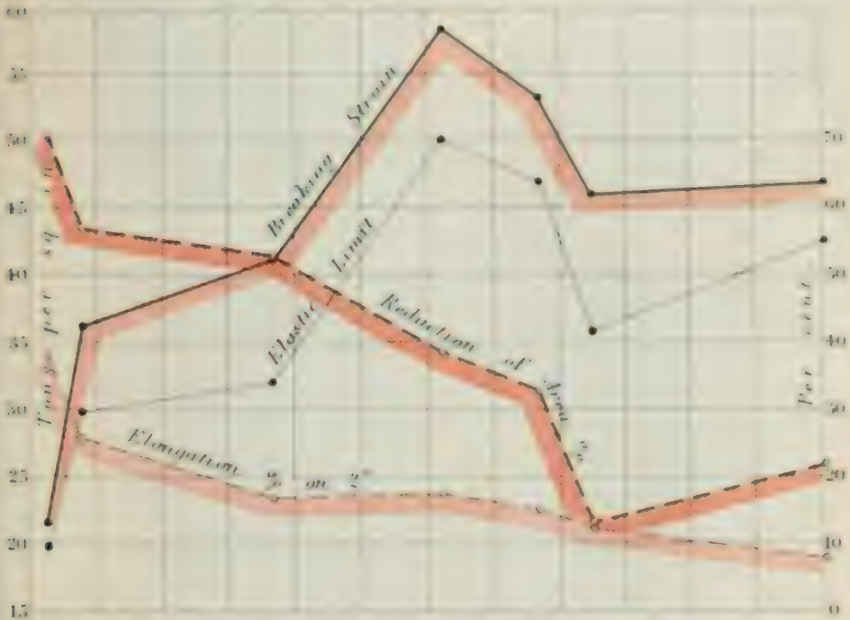
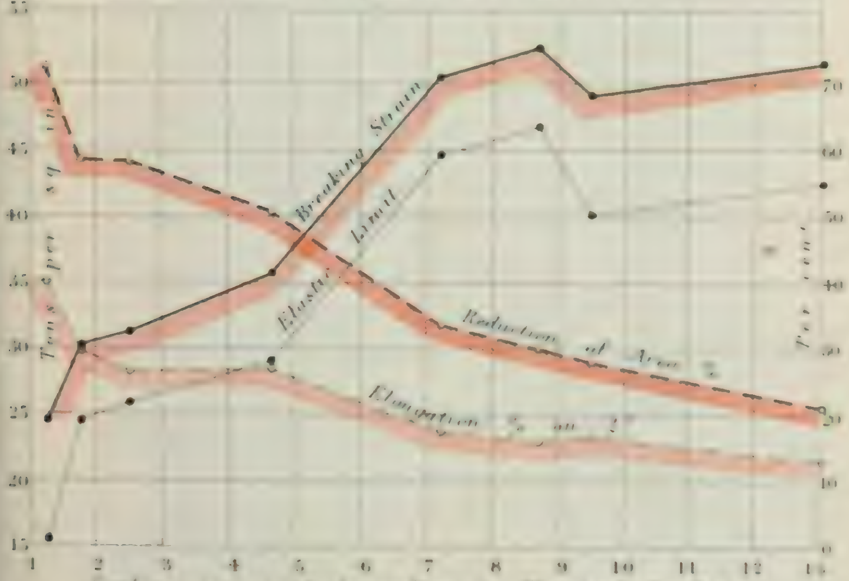
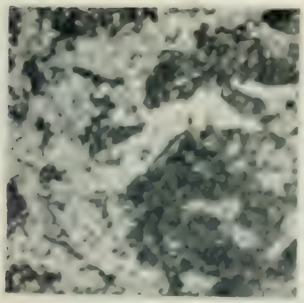


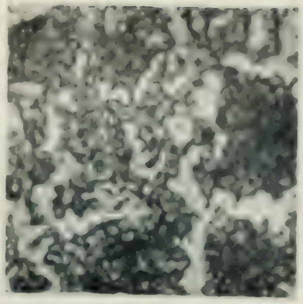
Fig 27 *Steels quenched from 900° C (1,652° F) in Oil, and Reheated to 600° C (1,112° F)*

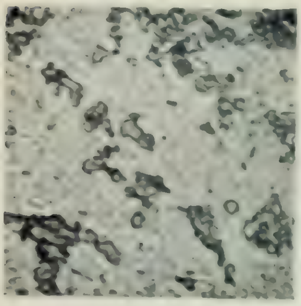


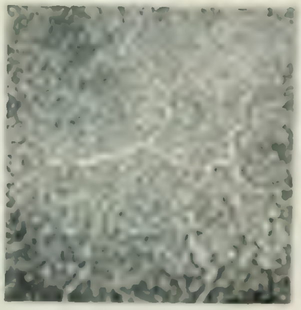
Carbon per cent according to Chemical Analysis; Mechanical Engineers 1904.

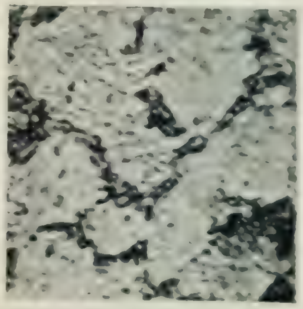
ALLOYS RESEARCH. Plate 17.

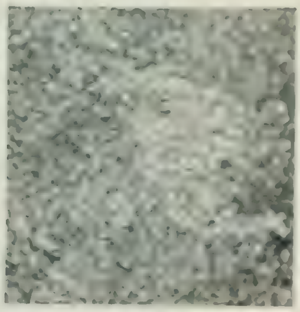


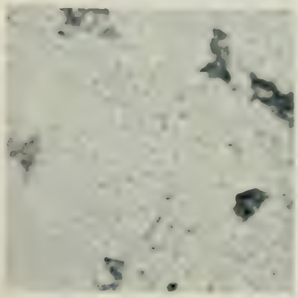












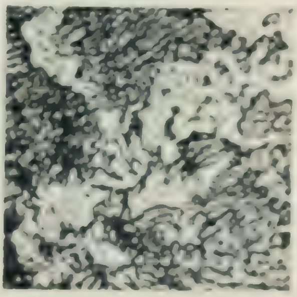


Photo-Micrographs of Steel Bars as received (Rolled) × 1,000 diams.

Mechanical Engineers 1904.

Steel Bars, after annealing for ½ hour at 620° C. (1,148° F.). × 1,000 diams.

Fig. 36. [illegible]

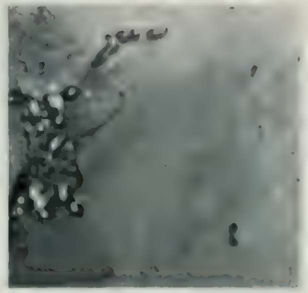


Fig. 37. 0·19 % C.

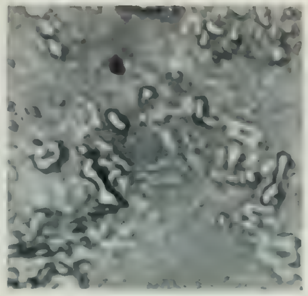


Fig. 38. [illegible]

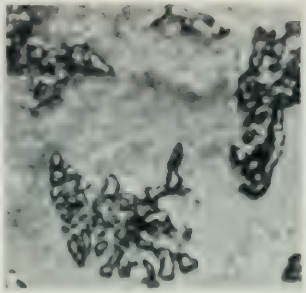


Fig. 39. [illegible]

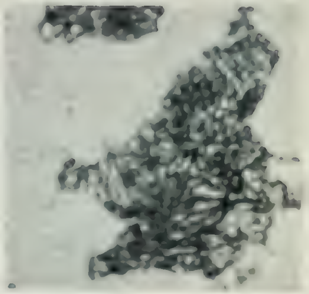


Fig. 40. [illegible]

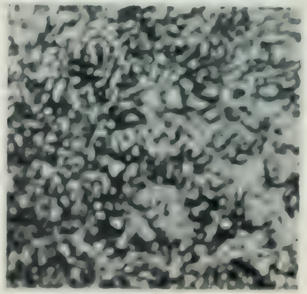


Fig. 41. [illegible]

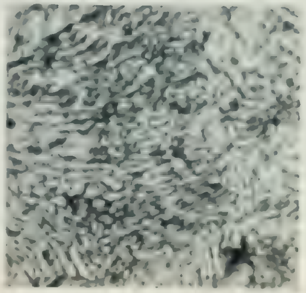


Fig. 42. [illegible]

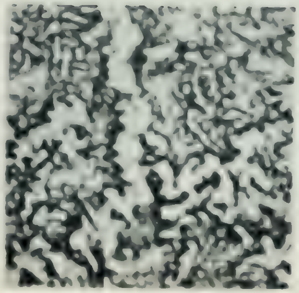
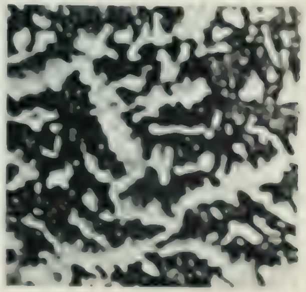


Fig. 43. [illegible]



Steel Bars, after annealing for ½-hour at 720° C. (1,328° F.) × 1,000 diams.

Fig. 44. 0·19% C

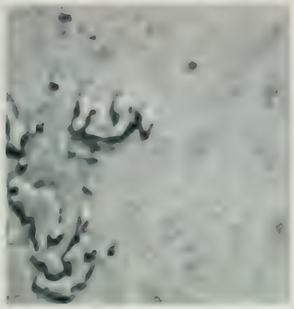


Fig. 45. 0·18% C

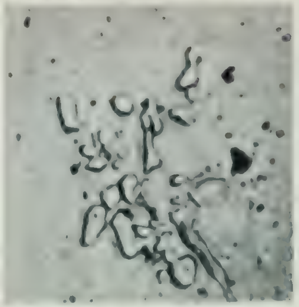


Fig. 46. 0·24% C

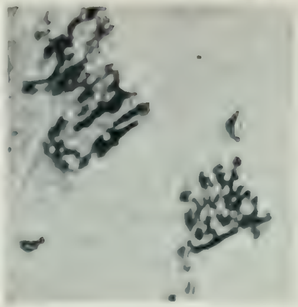


Fig. 47. [illegible]

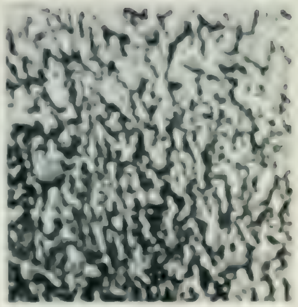


Fig. 48. 0·72% C

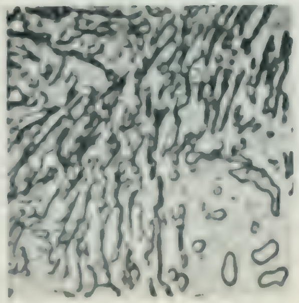


Fig. 49. 0·85% C

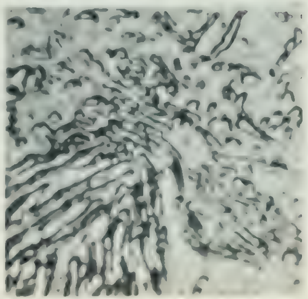


Fig. 50. 0·91% C

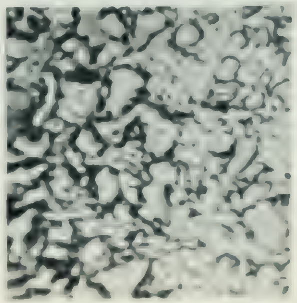
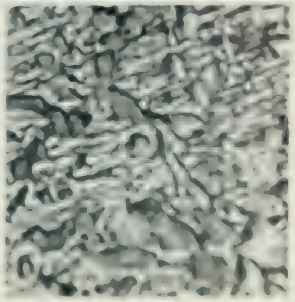


Fig. 51. 1·00% C



Steel Bars, after annealing for ½-hour at 800° C. (1,472° F.) × 1,000 diams.

Fig. 52. 0·13% C.

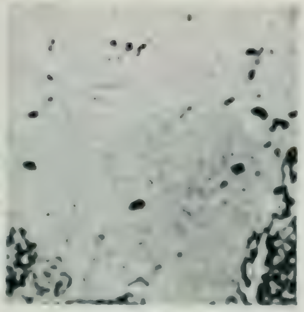


Fig. 53. 0·18% C.

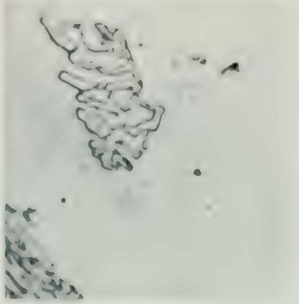


Fig. 54. 0·254% C.

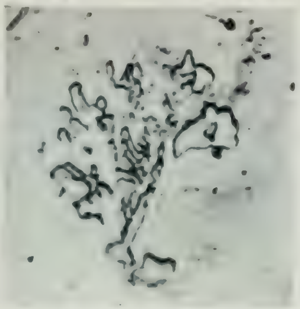


Fig. 55. 0·40% C.

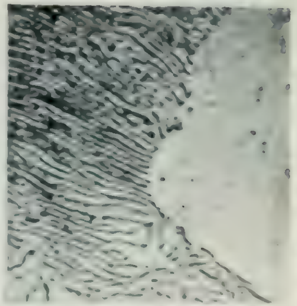


Fig. 56. 0·72% C.

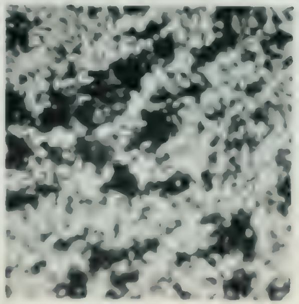


Fig. 57. 0·87% C.

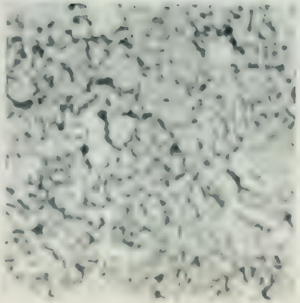


Fig. 58. 0·94% C.

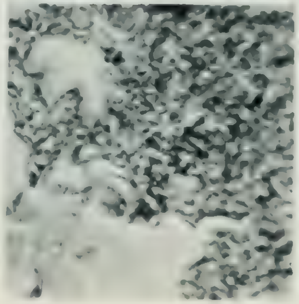
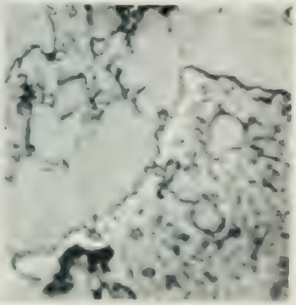
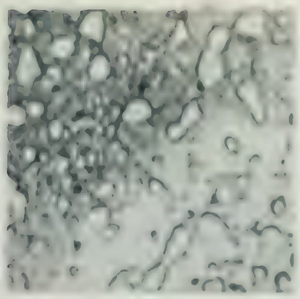
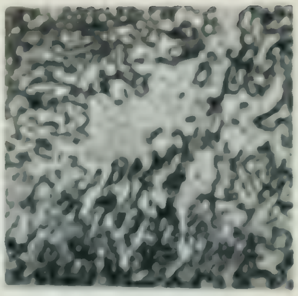
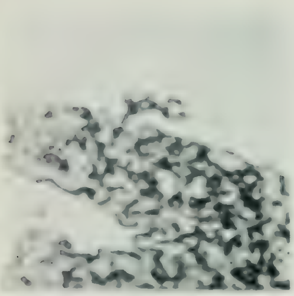


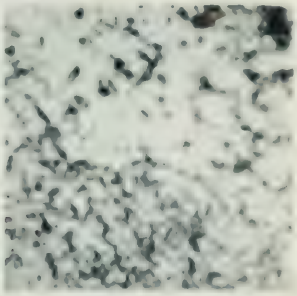
Fig. 59. [illegible]

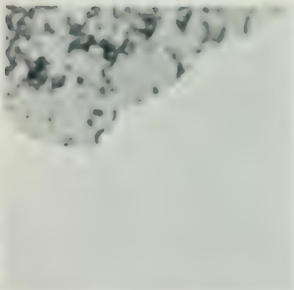


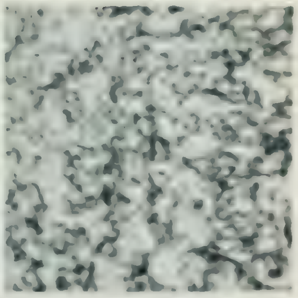


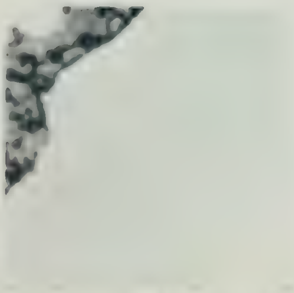


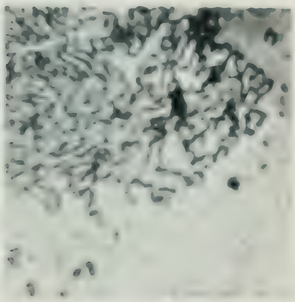












Steel Bars, after annealing for ½ hour at 900° C. 1,652° F. — 1,000 diam.

Mechanical Engineers 1905

Steel Bars, after annealing for 10 minutes at 900° C. (1,652° F.) × 1,000 diam.

Fig. 68. *0·15% C.*

Fig. 69. *0·18% C.*

Fig. 70. *0·25% C.*

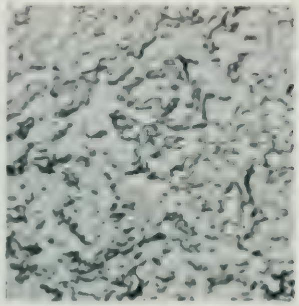


Fig. 71. *0·46% C.*

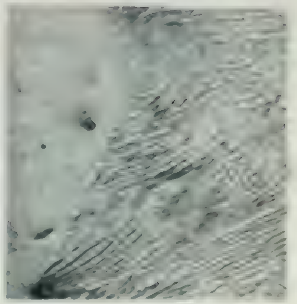


Fig. 72. *0·52% C.*

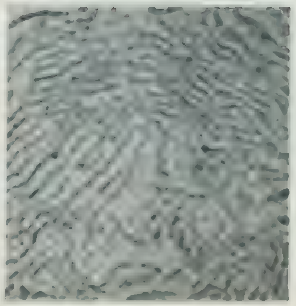


Fig. 73. *0·87% C.*

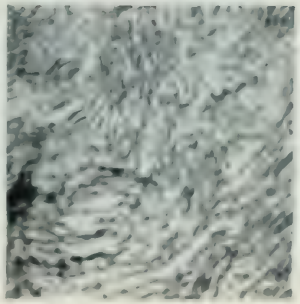


Fig. 74. *0·97% C.*

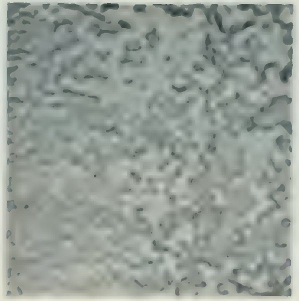
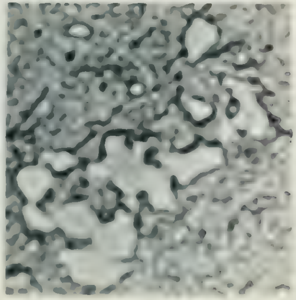


Fig. 75. *1·30% C.*



Steel Bars, after annealing for ½-hour at 1,100° C. (2,012° F.) × 1,000 diams.

Fig. 76. 0·165 C.

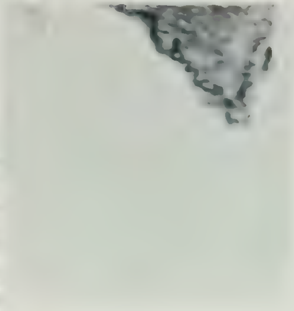


Fig. 77. 0·185 C.

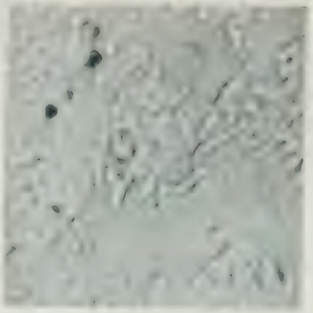


Fig. 78. 0·234 C.

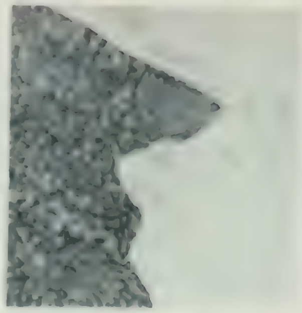


Fig. 79. 0·365 C.

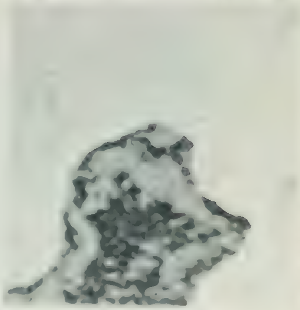


Fig. 80. 0·325 C.

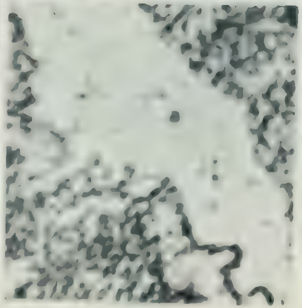


Fig. 81. 0·575 C.

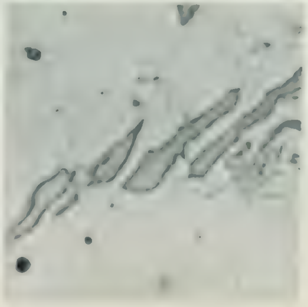


Fig. 82. 0·975 C.

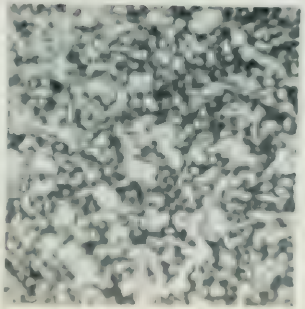
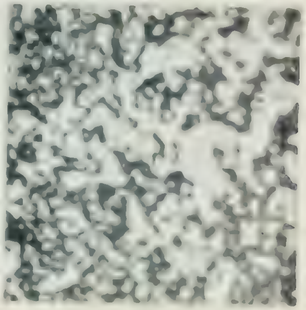


Fig. 83. 1·000 C.



Steel Bars, after soaking for 12 hours at 620° C. (1,148° F.) × 1,000 diams.

Fig. 84. 0·15% C.

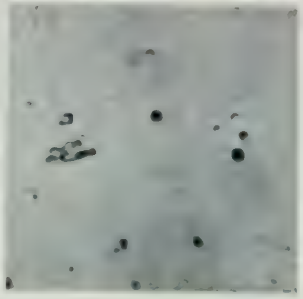


Fig. 85. 0·18% C.

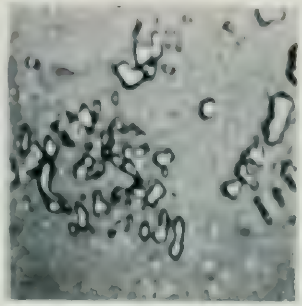


Fig. 86. [illegible] C.

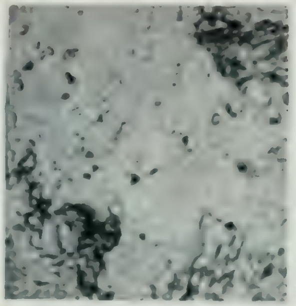


Fig. 87. [illegible] C.

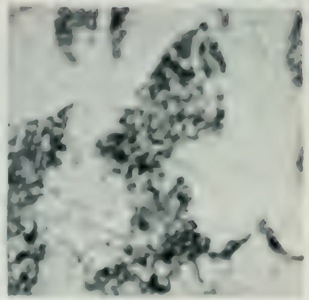


Fig. 88. [illegible] C.

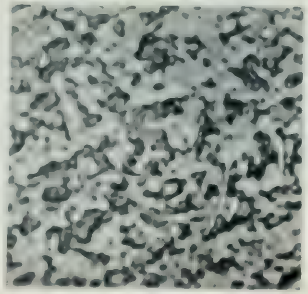


Fig. 89. 0·87% C.

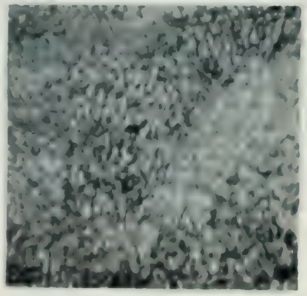


Fig. 90. 0·93% C.

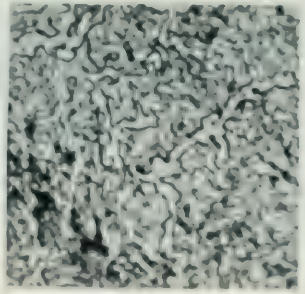
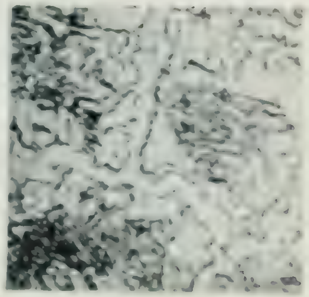


Fig. 91. [illegible] C.



Steel Bars, after soaking for 12 hours at 720° C. (1,328° F.)

× *140 diams.*

Fig. 92 *0·15% C.*

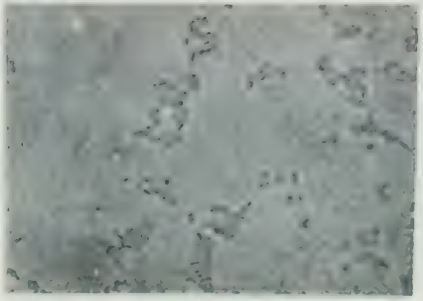


Fig. 93. *0·18% C.*

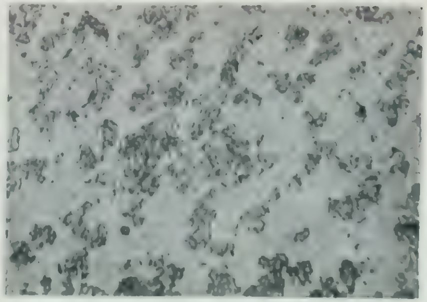
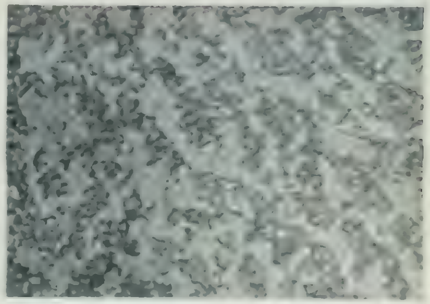


Fig. 94. *0·465% C.*



× *1,600 diams.*

Fig. 95. *0·722% C.*

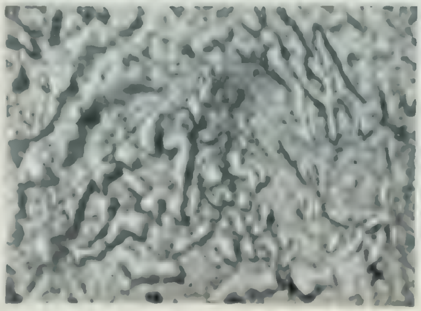


Fig. 96. *0·871% C.*

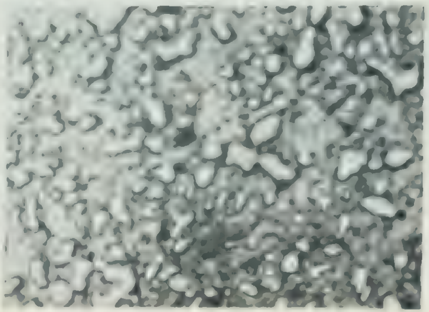
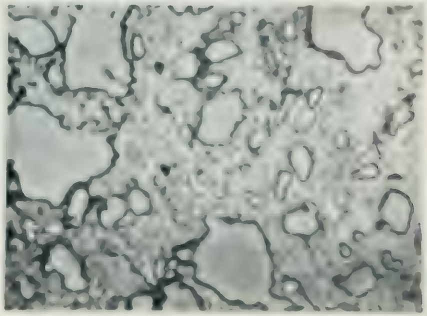


Fig. 97. *1·006% C.*



Steel Bars after quenching in Water at 900° C. (1,652° F.) × 1,000 diam.

Fig. 98. 0·722% C.

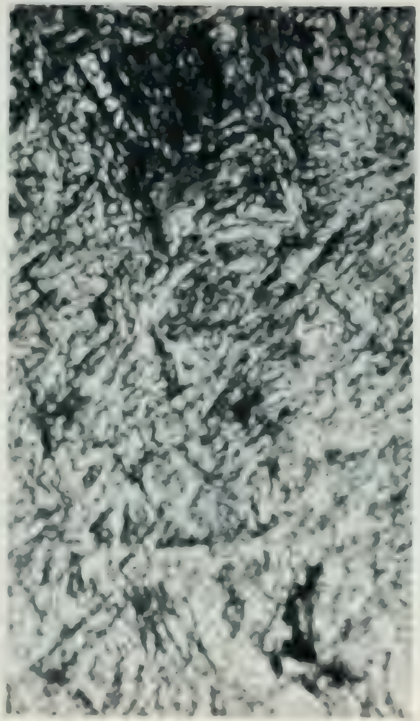


Fig. 99. 0·947% C.

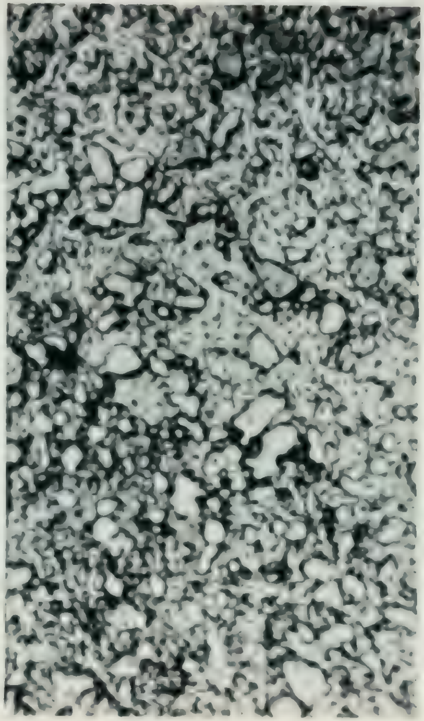
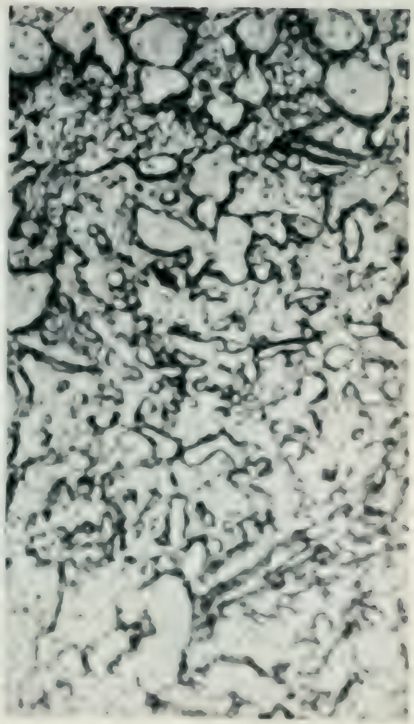


Fig. 100. 1·06% C.



Steel Bars, after quenching in Water at 1,200° C. (2,192° F.)
× 140 diams.

Fig. 101. *0·722% C.*

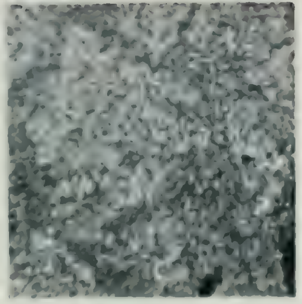


Fig. 102. *0·817% C.*

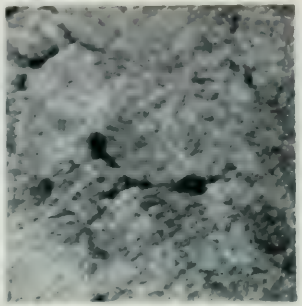


Fig. 103. *0·915% C.*

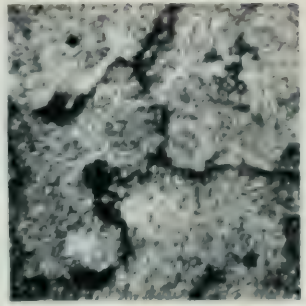
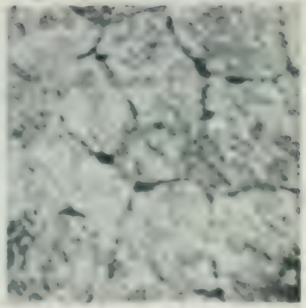


Fig. 104. *1·209% C.*



× 1,600 diams.

Fig. 105. *0·722% C.*

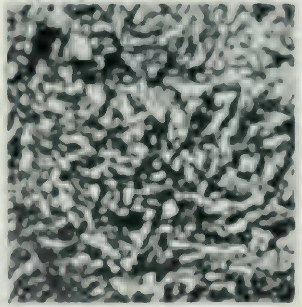


Fig. 106. *0·817% C.*

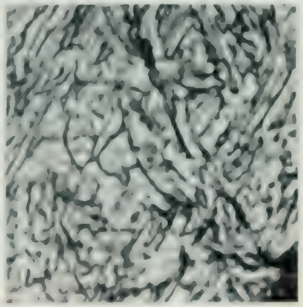


Fig. 107. *0·915% C.*

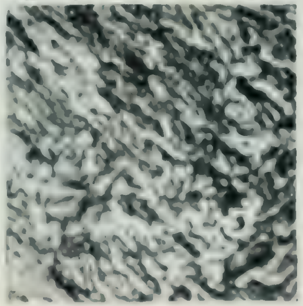
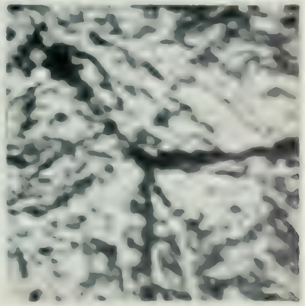


Fig. 108. *1·209% C.*



Steel Bars, after quenching in Oil at 870° C. (1,598° F.) and then Reheated to 350° C. (662° F.) × 1,000 diams.

Fig. 109. 0·15% C.

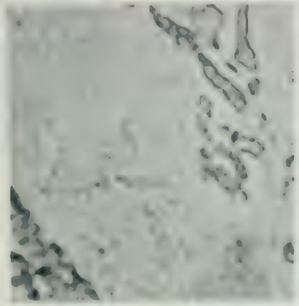


Fig. 110. 0·18% C.

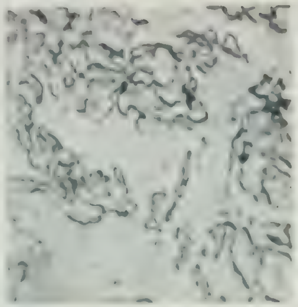


Fig. 111. 0·21% C.

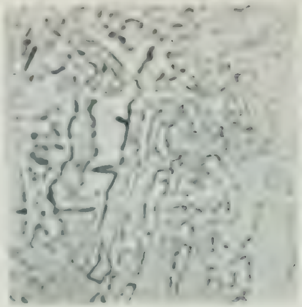


Fig. 112. 0·46% C.

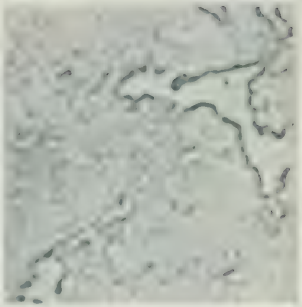


Fig. 113. 0·72% C.

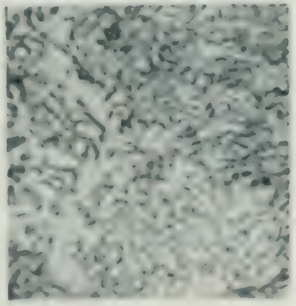


Fig. 114. 0·85% C.

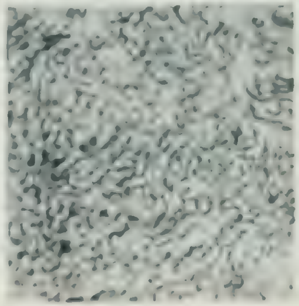


Fig. 115. 0·96% C.

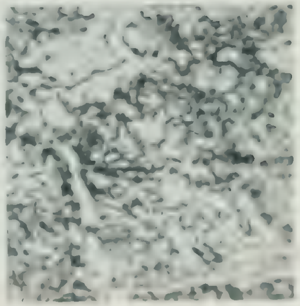
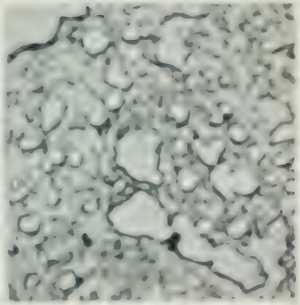


Fig. 116. 1·20% C.

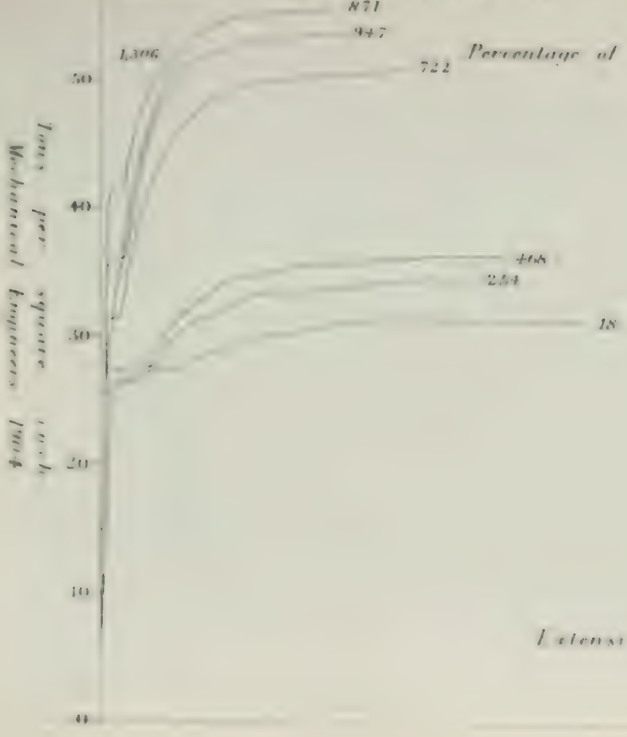


Mechanical Engineers 1904.

Steel Bars

Fig 118

Annealed at 620° C (1,148° F) for ½ hour

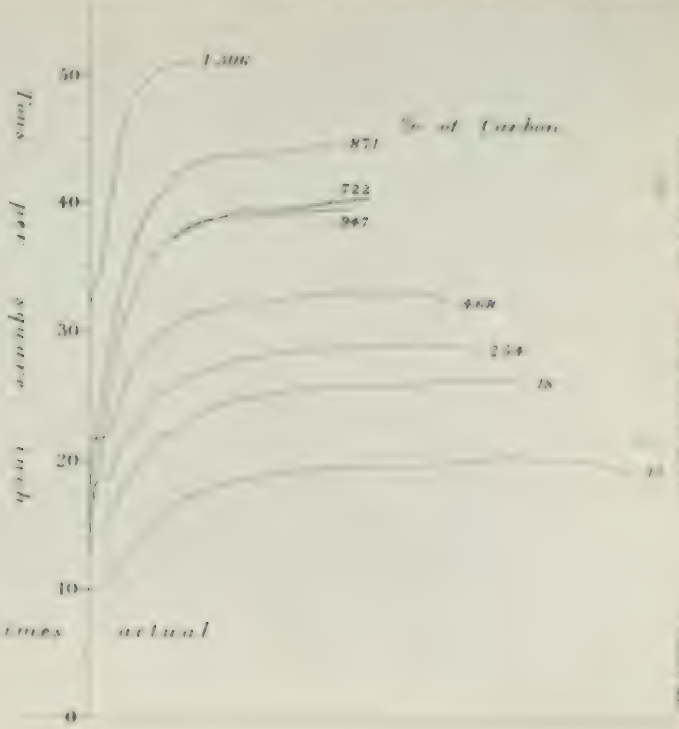


Mechanical Engineers 1904

Extensions 3 times actual

Fig 119

Annealed at 720° C (1,328° F) for ½ hour



Steel Bars.

Fig 120

Annealed at 800° C (1,472° F.) for ½ hour

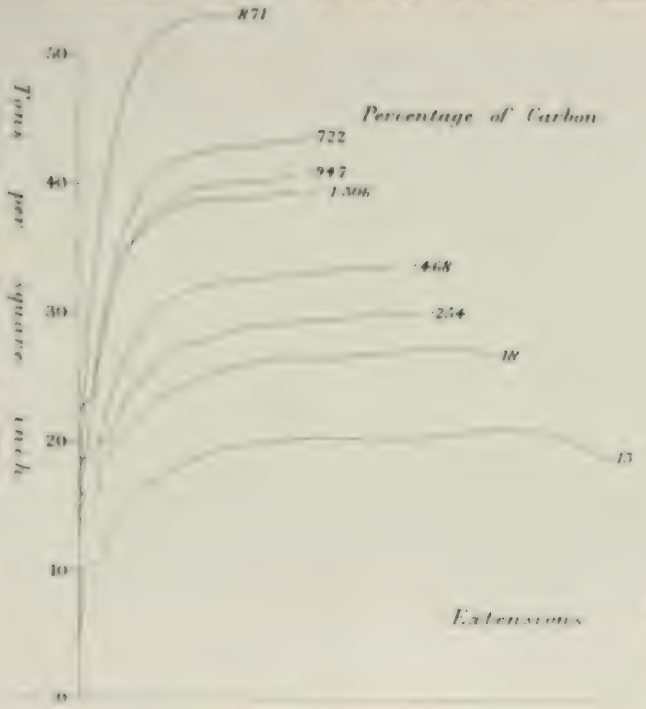
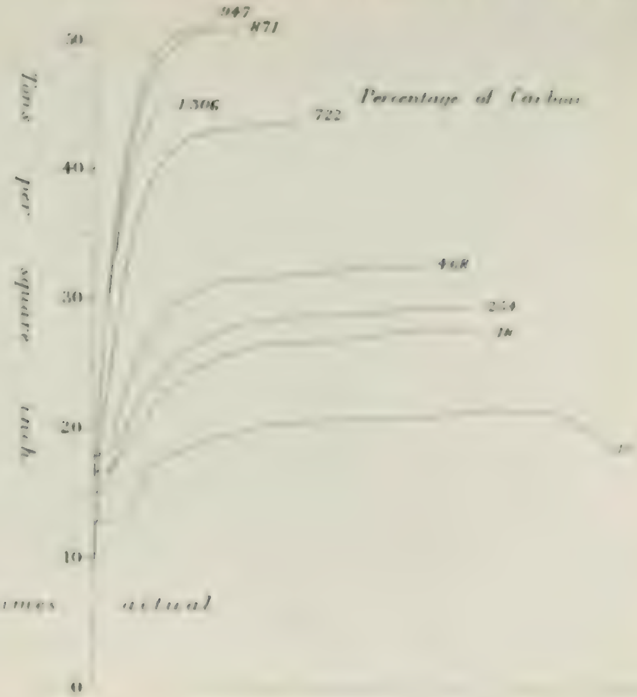


Fig 121

Annealed at 900° C (1,652° F.) for ½ hour

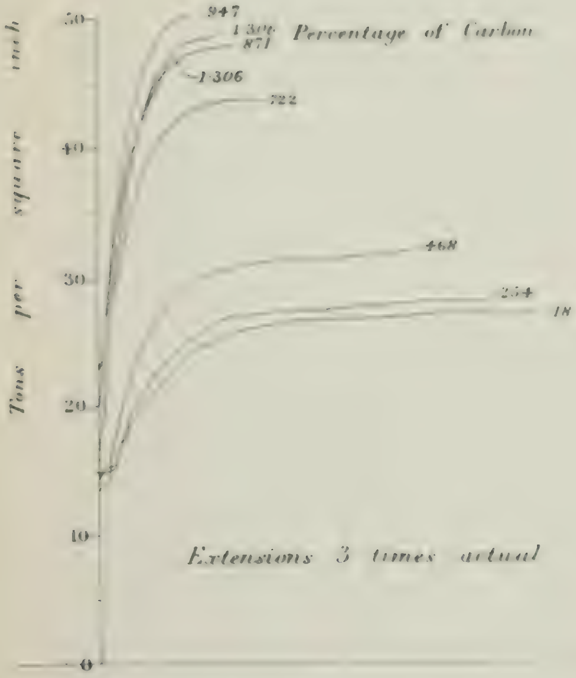


Extensions 3 times actual

Steel Bars

Fig. 122

Annealed at 1100° C (2,012°F) for ½ hour



ALLOYS RESEARCH.

Steel Bars

Fig 123

Quenched at 720° C

(1,328° F) *in Water*

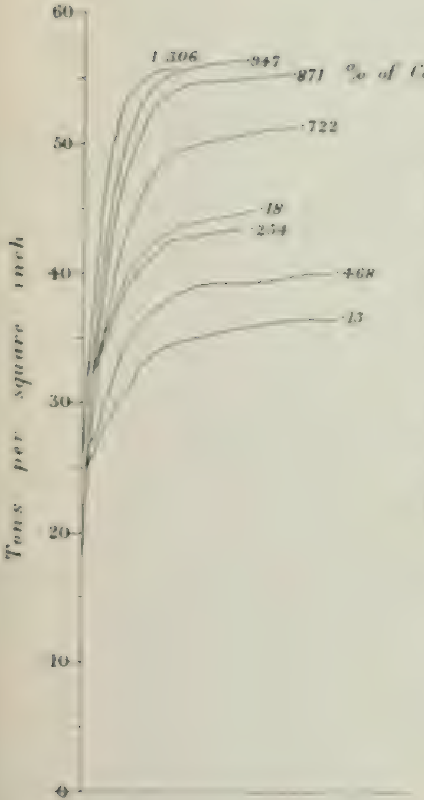
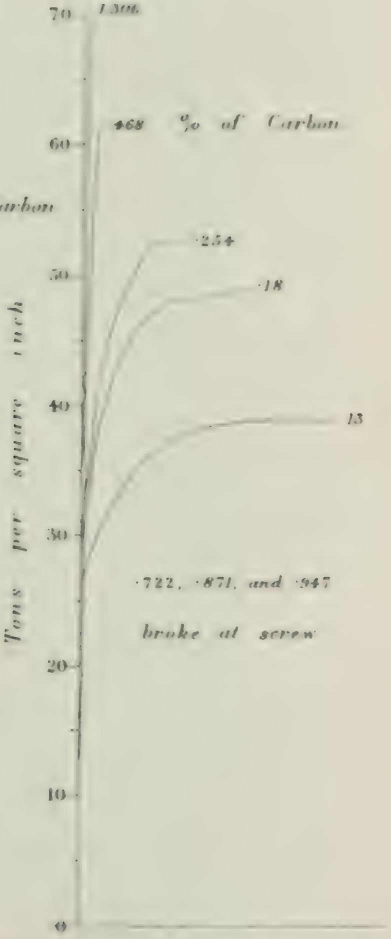


Fig 124

Quenched at 800° C

(1,472° F) *in Water*



·722, ·871, and ·947

broke at screw

Extensions 3 times actual

Mechanical Engineers 1904

Steel Bars

Fig 125

Quenched at 900° C (1,652° F) in Water

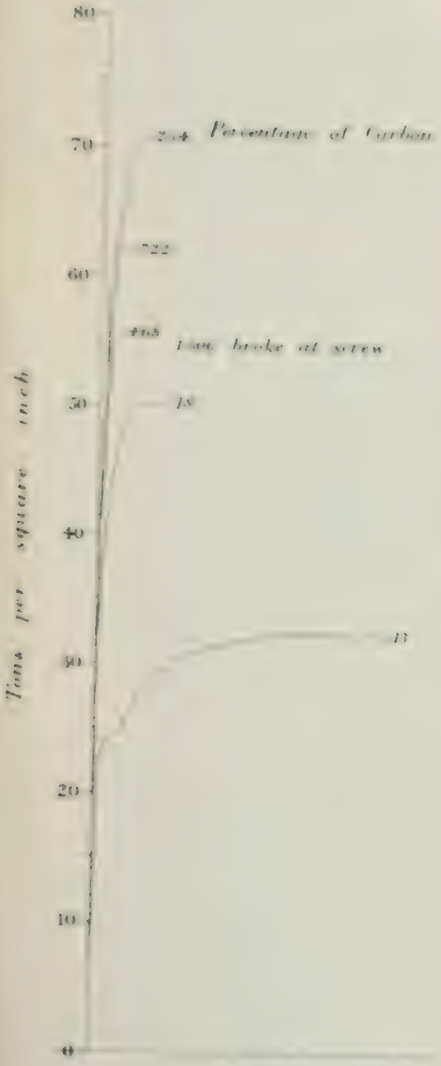
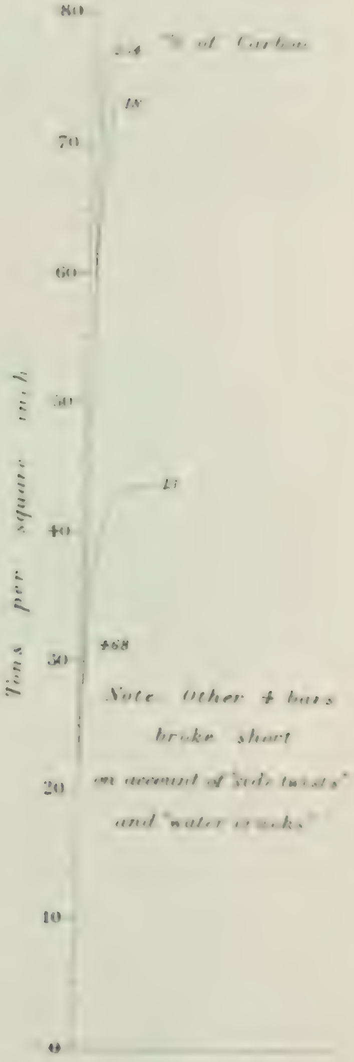


Fig 126

Quenched at 1200° C (2,192° F) in Water



Note. Other 4 bars broke short on account of "side twists" and "water cracks."

Extensions 3 times actual

Heat Treatment of High Carbon Steel.

Fig. 127. Austenite produced by quenching 1·1% Carbon Steel in Cold Brine. ×1,000 diams.

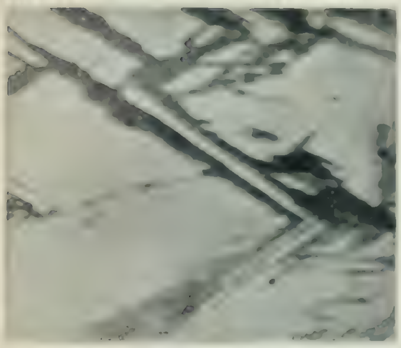


Fig. 128. Austenite transformed by immersing Steel in Liquid Air. ×1,000 diams.

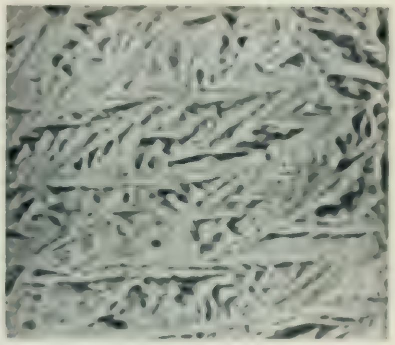


Fig. 129. Steel containing 1·1% Carbon. Air Cooled. ×1,000 diams.

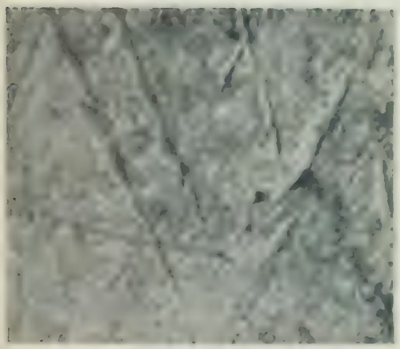


Fig. 130. Die Steel overheated before quenching in Water. ×1,000 diams.

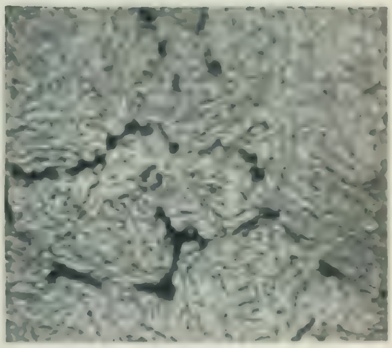


Fig. 131. Spring Steel for Safety Valve. Oil hardened. ×1,000 diams.

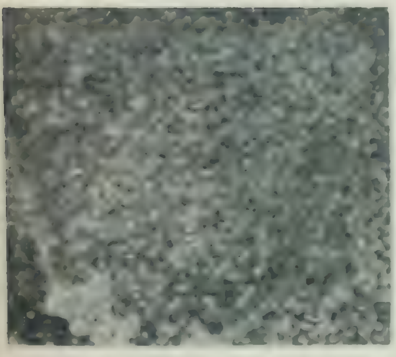
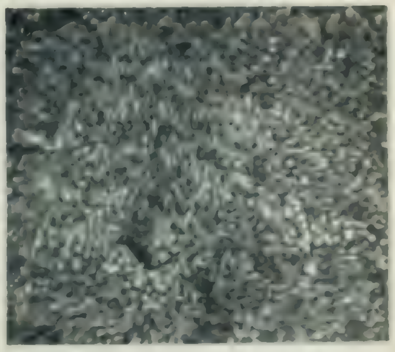


Fig. 132. Spindle containing 1·00% C. Oil hardened. ×1,000 diams.



Steel suitable for the Manufacture of Ordnance.

Fig. 133. *Steel as Cast.* × *20 diams.*

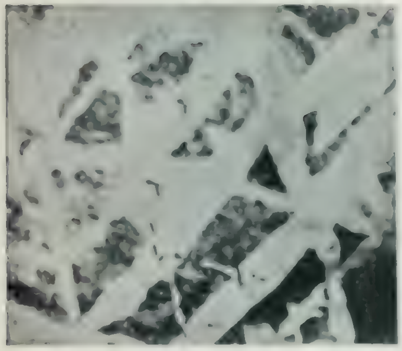


Fig. 134. *Steel annealed at 900° C. (1,652° F.)* × *140 diams.*

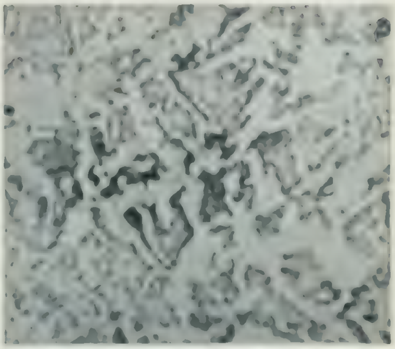


Fig. 135. *Exterior of Oil Treated "A" Tube of Gun.* × *140 diams.*

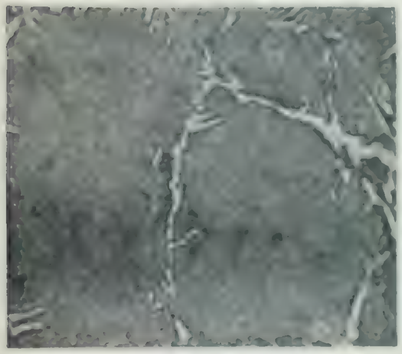


Fig. 136. *High-power of Carbide Area of Gun Steel.* × *1,000 diams.*

Fig. 137. *Interior of Oil Treated "A" Tube of Gun* × *140 diams.*

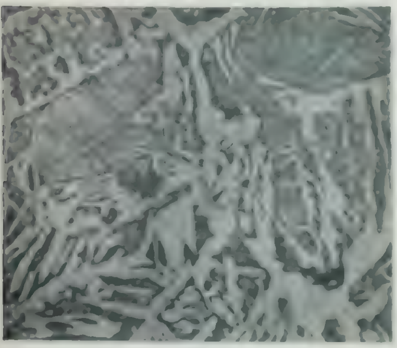
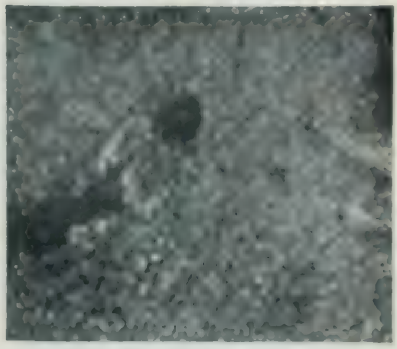


Fig. 138. *High-power of Carbide Area.* × *1,000 diams.*



Steels suitable for the Manufacture of Ordnance.

Fig. 139. *Steel Quenched at 730° C. (1,346° F.) in Water over Mercury. Showing Martensite and Ferrite. × 1,000 diams.*

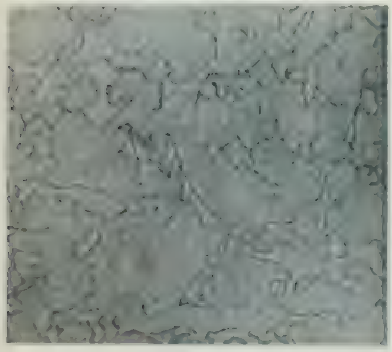


Fig. 140. *Steel Quenched in Water over Mercury from 730° C. (1,346° F.). × 300 diams.*

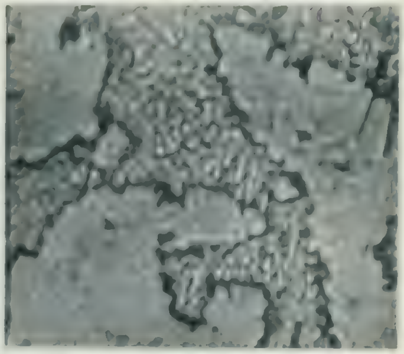


Fig. 141. *Steel Quenched in Water over Mercury. Showing Martensite and Ferrite. × 1,600 diams.*

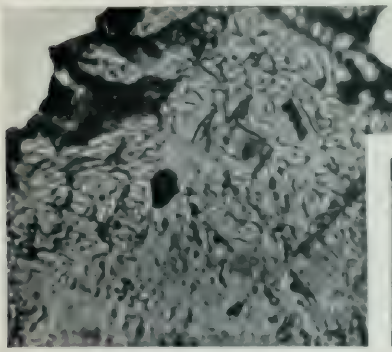
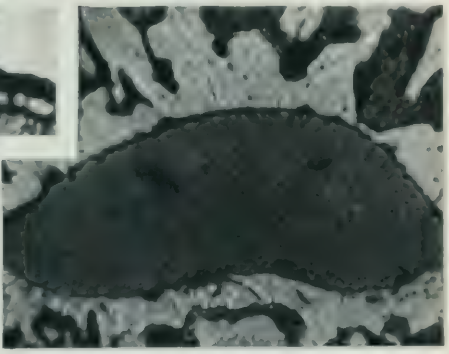


Fig. 142. *Manganese Sulphide Plate in Slowly Cooled Steel. × 300 diams.*



Very Mild Steel.

Fig. 143. *Structural Steel as Cast. × 140 diams.*

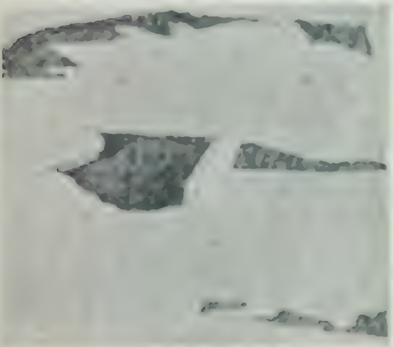
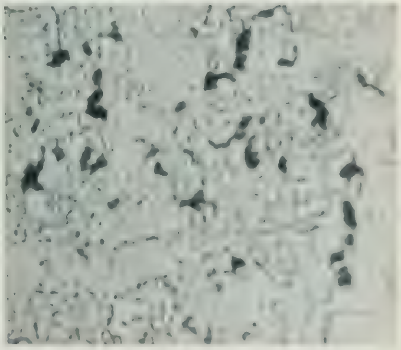


Fig. 144. *Structural Steel annealed to 800° C. (1,472° F.) and Cooled in Wood Ashes. × 140 diams.*



Ten-inch Axle containing 0·[illegible]% Carbon.

Quenched in Oil. × 110 diams.

Fig. 145. *Exterior of Axle.*

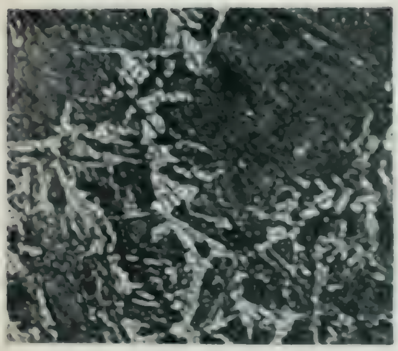


Fig. 146. *Section from No. 1 position.*

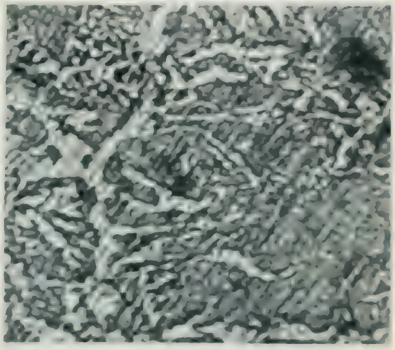


Fig. 147.
Section from No. 2 position.

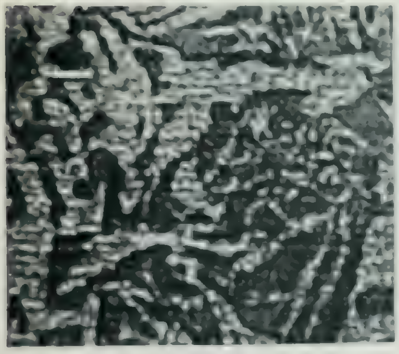


Fig. 148.
Section from No. 3 position.

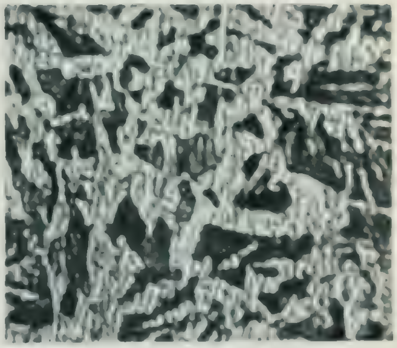


Fig. 149.
Section from No. 4 position.

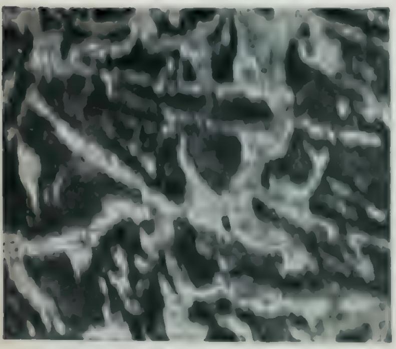
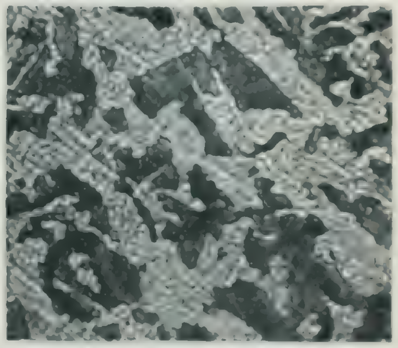


Fig. 150.
Centre of Axle.



Cutting Edge of a Cast-Iron Tool from Principal Workshop of the Pennsylvania Railroad Co. in Altoona.

Fig. 151. *Cementite and Modified Martensite.* × 100 diams.

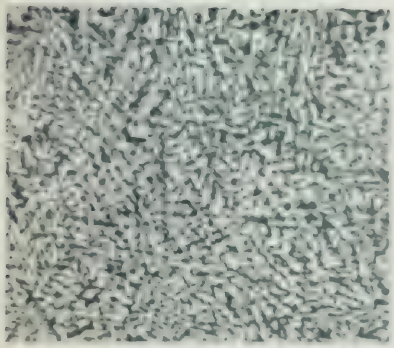


Fig. 152. *Cementite and Modified Martensite.* × 1,000 diams.

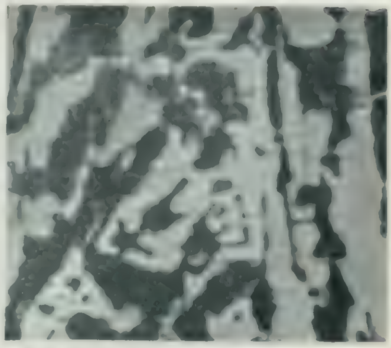


Fig. 153. *Cementite and Modified Martensite.* × 100 diams.

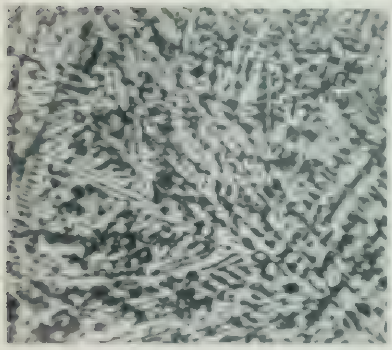
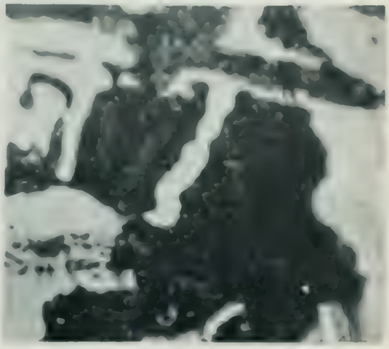


Fig. 154. *Cementite and Martensite, etched in painting [illegible].* × 1,000 diams.



Steel Spindles.

Fig. 155. *Good Spindle.*

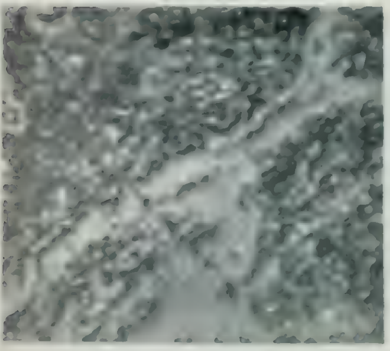
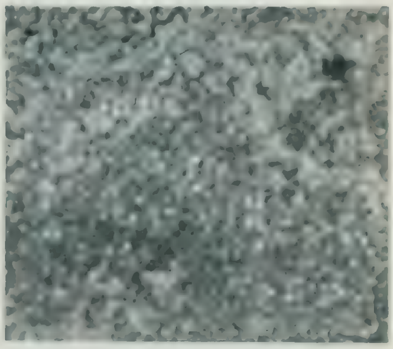


Fig. 156. *Bad Spindle.*



Miscellaneous Photo-Micrographs.

Fig. 157. *[illegible] 0·2% Carbon, Quenched in Mercury.* ×2,000 diams.

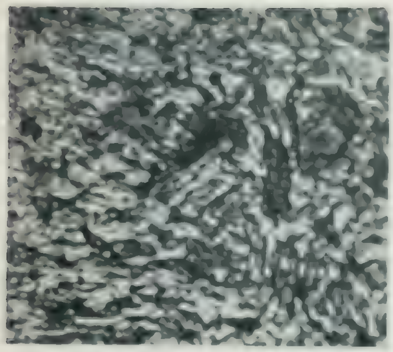


Fig. 158. *Tempered at 500° C. (932° F.) for 1,000 hours.* ×2,000 diams.

Fig. 159. *Burnt Steel Slowly Cooled 0·85% Carbon.* ×140 diams.

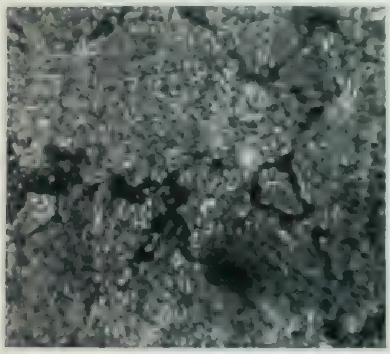


Fig. 160. *Burnt Steel Slowly Cooled 0·85% Carbon.* ×840 diams.

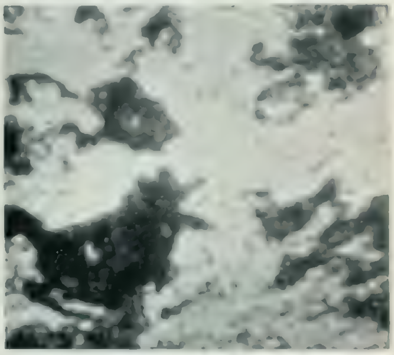


Fig. 161.
Cold Rolling of Steel Rail.
×250 diams.

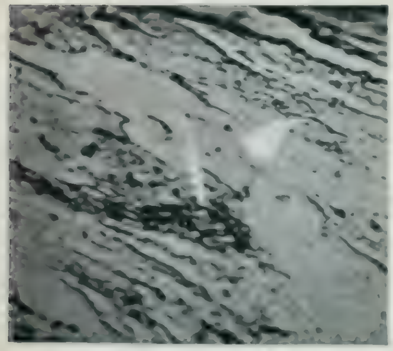
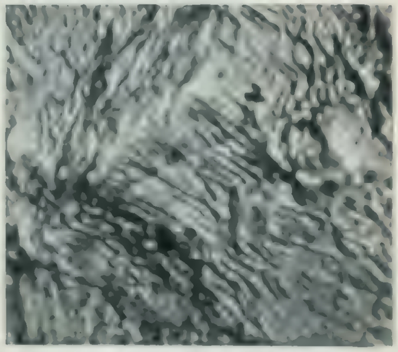


Fig. 162. *Pearlite Structure made evident by squeezing a Dead-soft Steel.* ×1,000 diams.



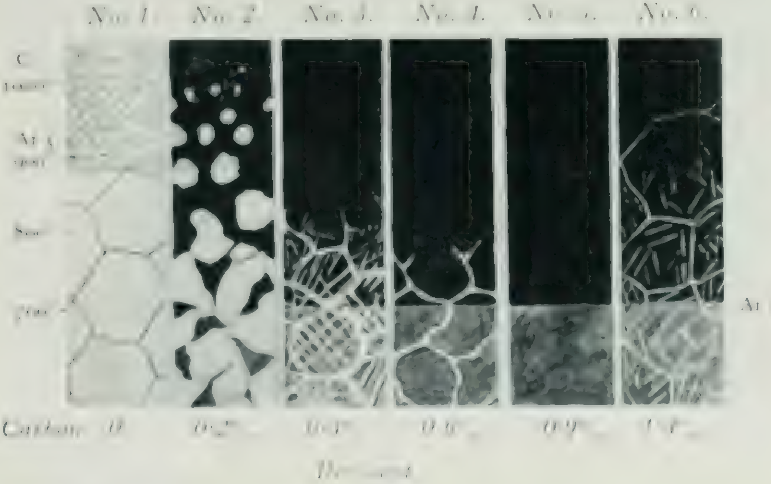
Mechanical Engineers 1904.

ALLOYS RESEARCH.

[illegible]

Fig. 163. *Diagrammatic Chart.*

Micro-sections of Steel with varying Carbon, heated to 1,000° C. (1,832° F.) at upper end and kept below 670° C. (1,238° F.) at other, then quenched in cold water.



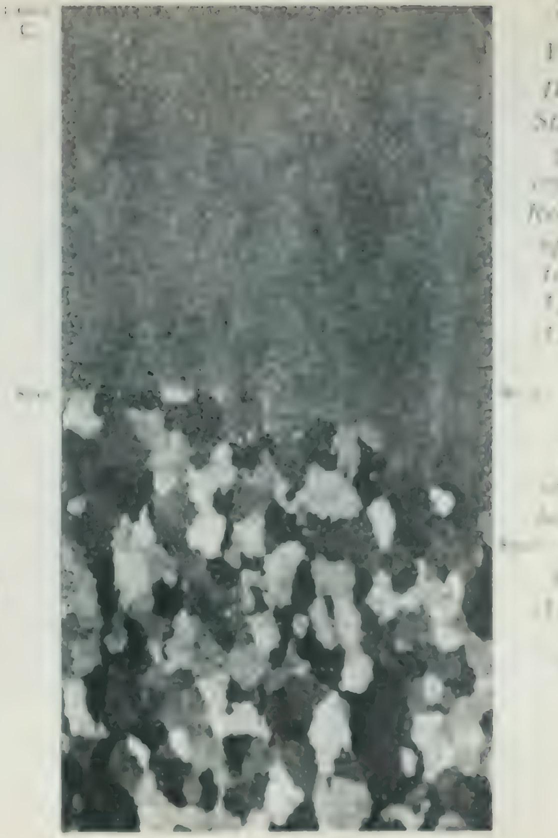


Fig. 164

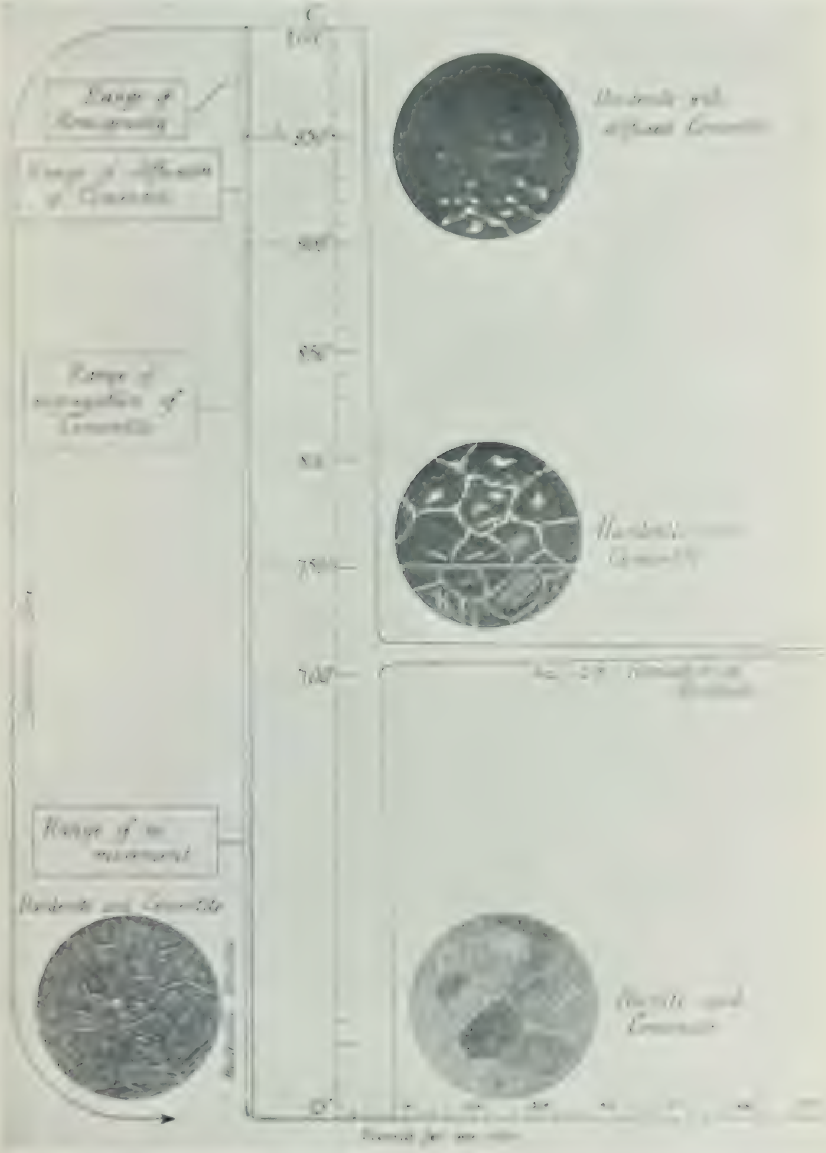
Dead-soft Steel Sheet grossly crystalline. Reheated at upper end to nearly 1,000° C. (1,832° F.)

The other end below 650° C. (1,202° F.) Full size.

Mechanical Engineer 1904.

[illegible]

Fig. 105. *Results of Heating and Quenching (but not Soaking) a Supersaturated Steel containing 1·2% Carbon.*



Mechanical Engineers 1904.

Fig. 166. St. Neots Rail, showing Martensite and Ferrite Grains at its running edge. × 140 diams.

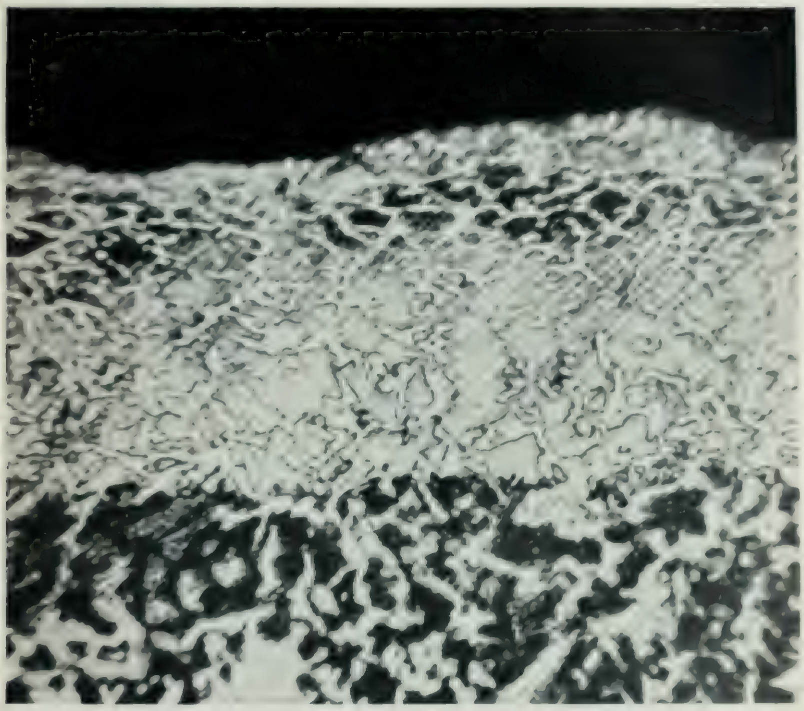


Fig. 167. St. Neots Rail, imitated by "arcing" the running edge of a normal rail. Martensite and Ferrite are visible in juxtaposition. × 140 diams.

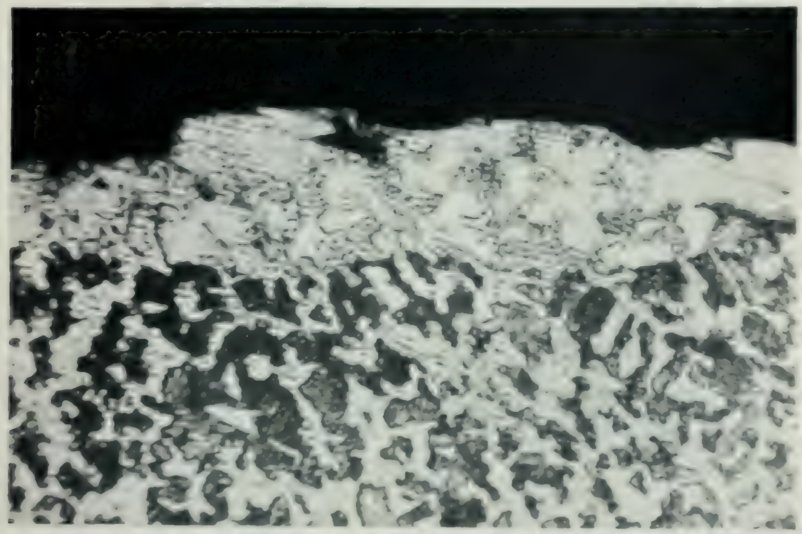
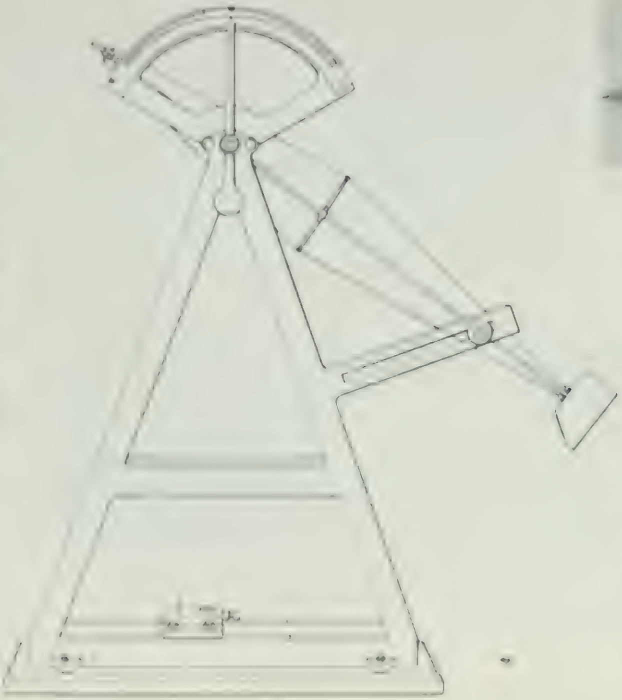


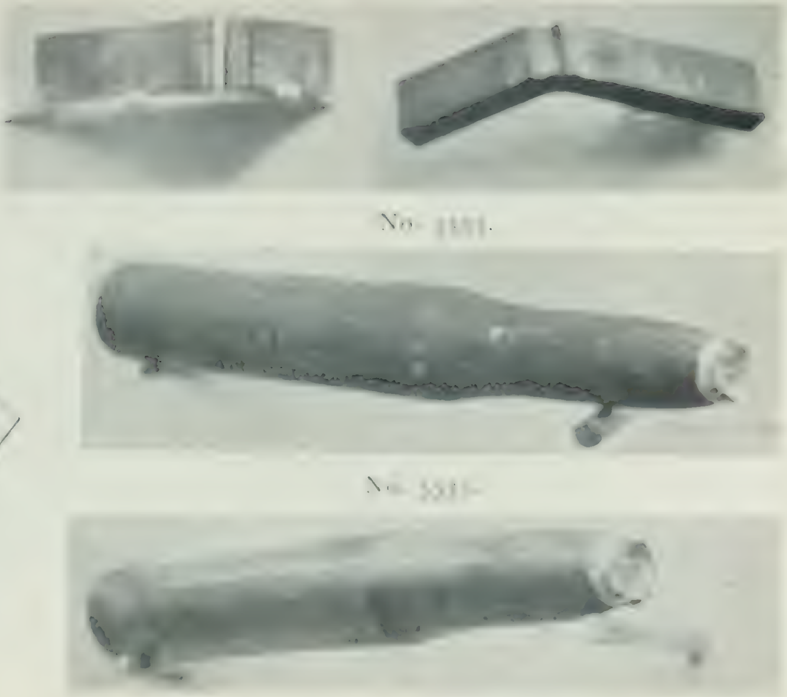
Fig. 170.

Impact Testing Machine.
Pendulum type.



Mechanical Engineer 1904.

Fig. 171. *Test Pieces.*



No. [illegible]

No. [illegible]

No. 1891.

No. [illegible]

Malleable Iron Castings.

Fig. 193. *Original Bar. Polished. × 3 diams.*

Fig. 194. *Original Bar showing Cementite, Pearlite and Sorbite. × 1,000 diams.*

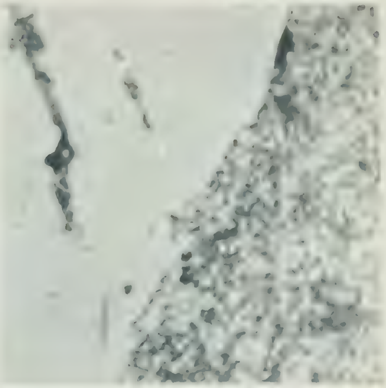


Fig. 192. *Coal-fired Annealing Furnace.*

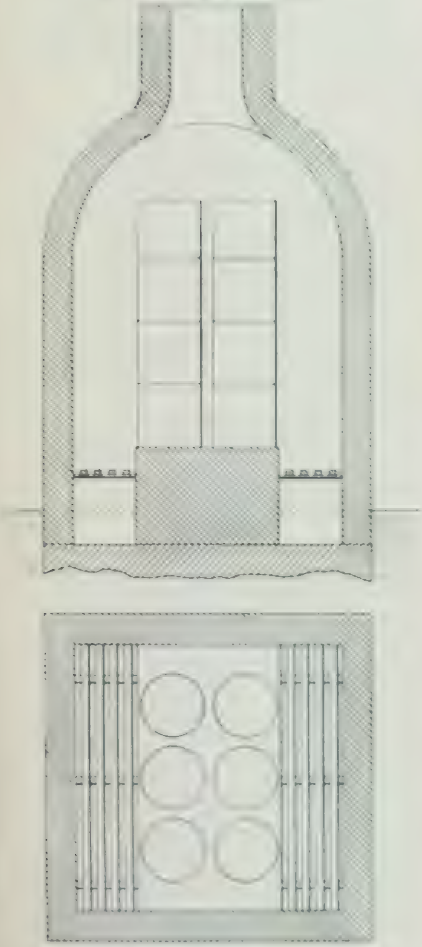


Fig. 195. *After Annealing Bar in Haematite. × 3 diams.*

Fig. 196. *Outside of Bar. × 1,000 diams.*

Mechanical Engineer 1904.

Series of Photo-micrographs of Malleable Iron Castings taken at equi-distant intervals from outside to centre of Bar. × 1,000 diams.

Fig. 197. *Second position.*

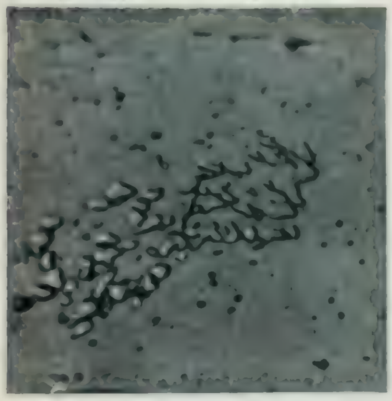


Fig. 198. *Third position.*

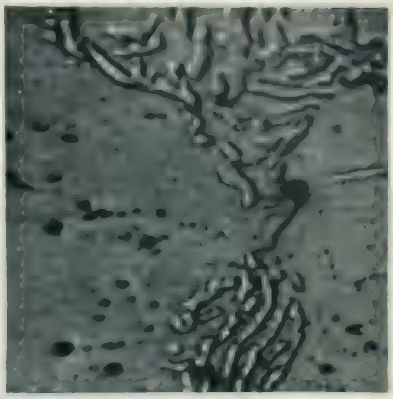


Fig. 199. *Fourth position.*

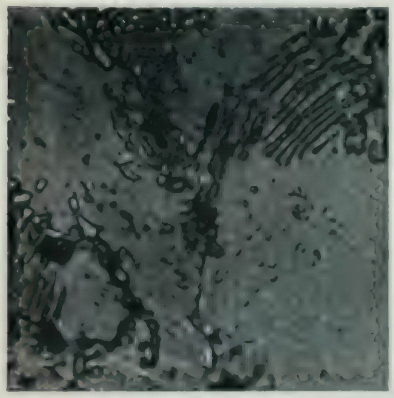


Fig. 200. *Fifth position.*

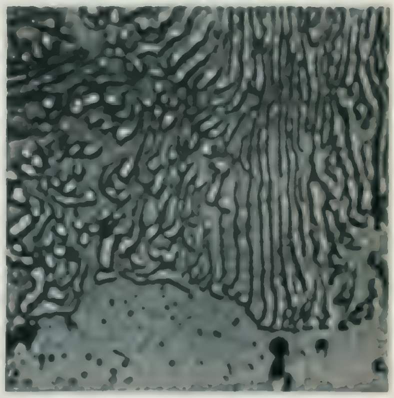


Fig. 201. *Sixth position.*

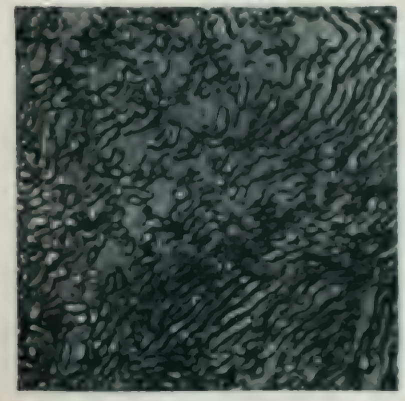
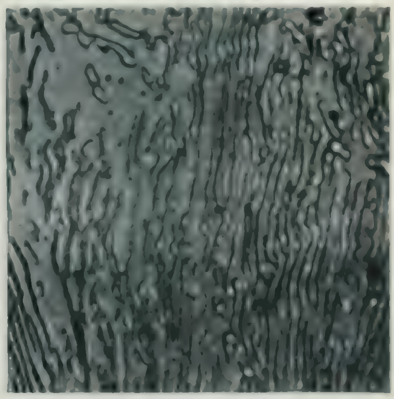


Fig. 202. *Seventh position.*



Series of Photo-micrographs of Malleable Iron Castings taken at equidistant intervals from outside to centre of Bar. × 1,000 *Diams.*

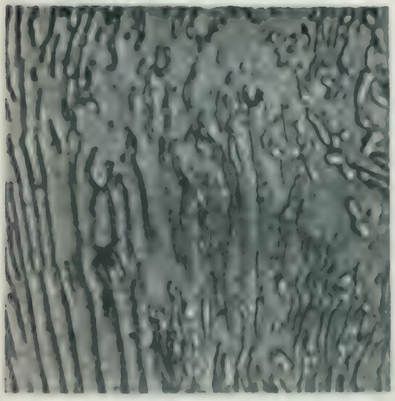


Fig. 203. *Eighth position.*

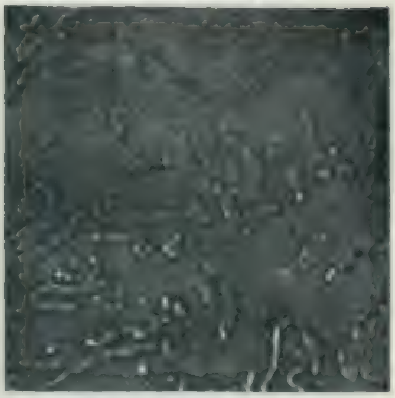


Fig. 204. *Ninth position.*

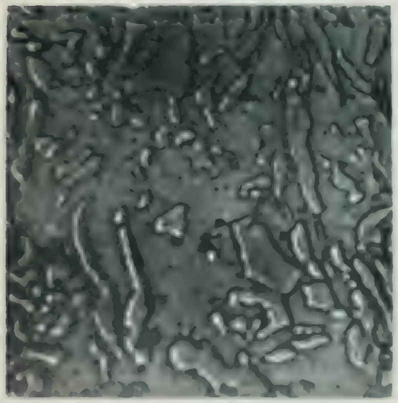


Fig. 205. *Tenth position.*

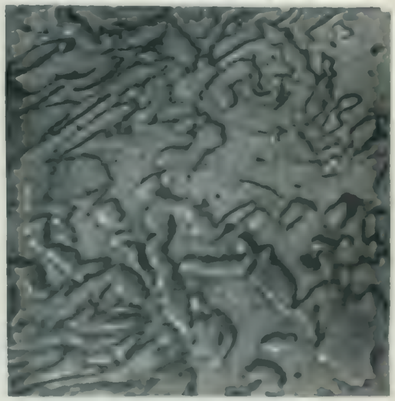


Fig. 206. *Eleventh position.*

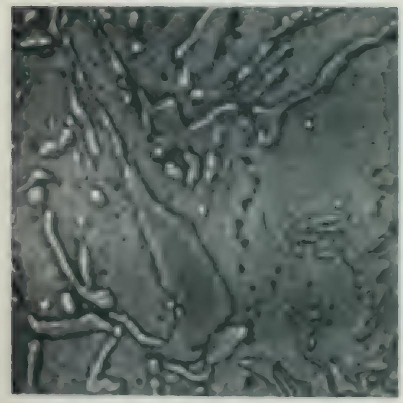


Fig. 207. *Twelfth position.*

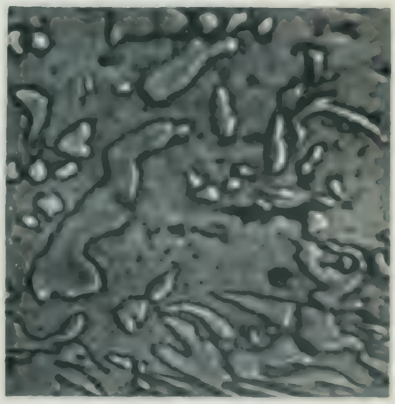
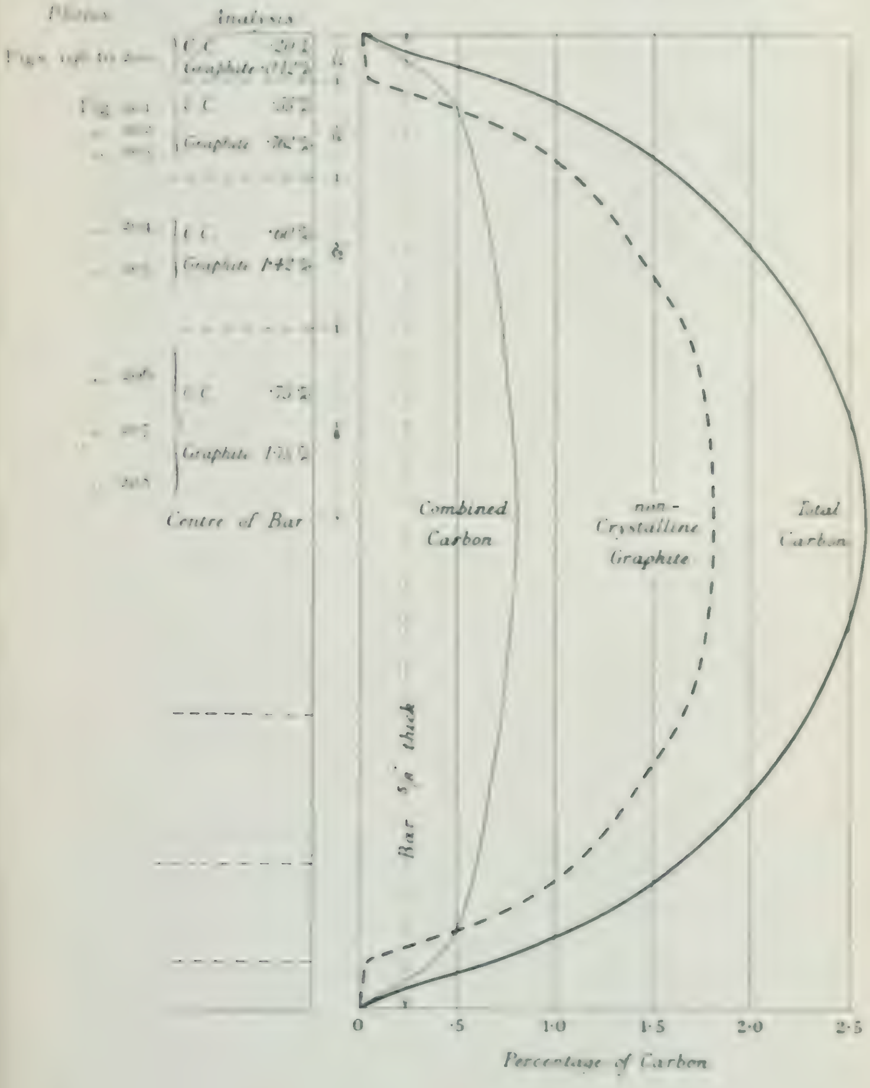


Fig. 208. *Centre of Bar.*

Malleable Iron Castings.

Fig. [illegible]

Diagram showing the Distribution of Carbon in the Annealed Bar.



Mechanical Engineers 1904.

Fig. 210. Freezing-point Curve of Tin-Antimony Alloys.

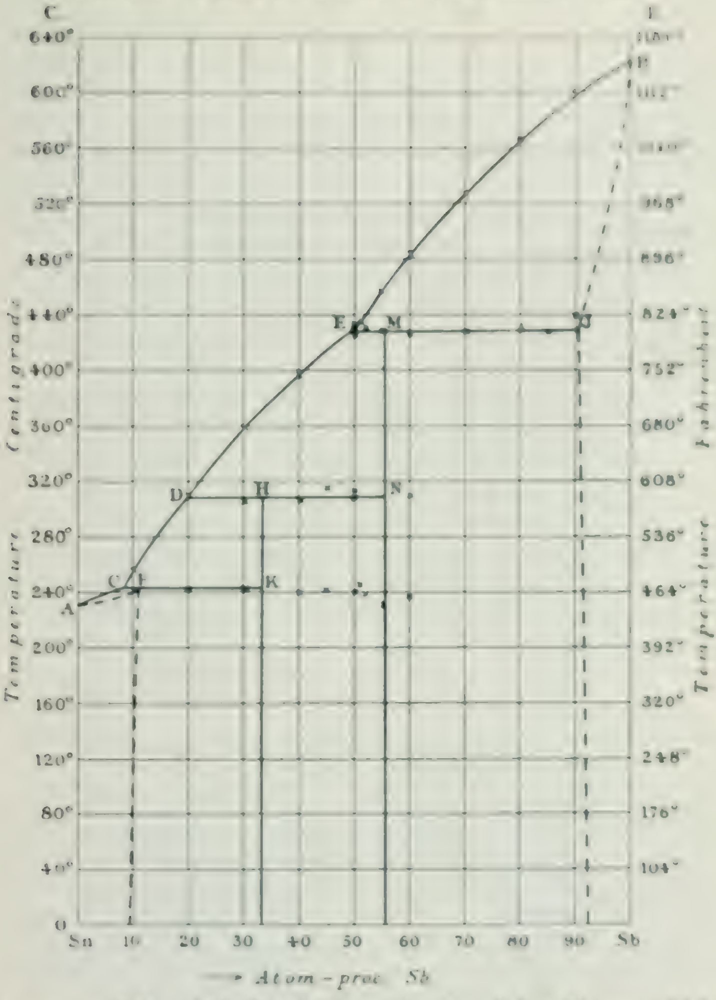
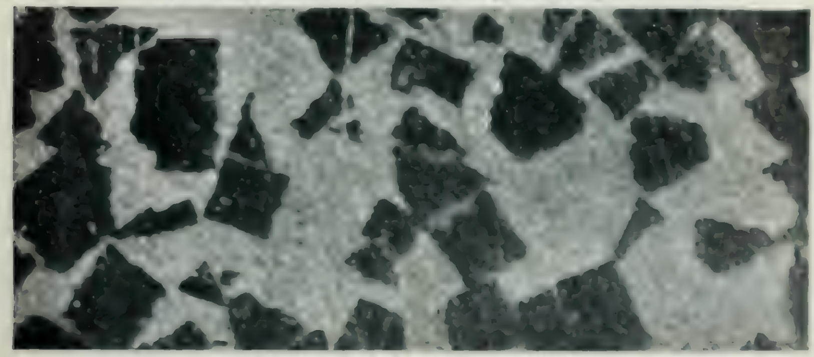


Fig. 211. Cubes of the Tin-Antimony Compound Sn_3Sb. × [illegible]



Mechanical Engineers 1901

TIN AND ANTIMONY.

Fig. 212. 20% Sb. × 40 diams.

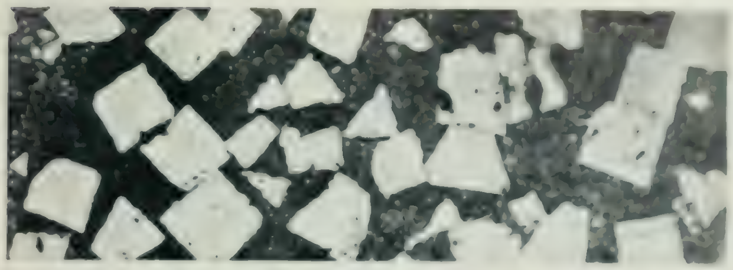


Fig. 213. 10% Sb. × 7 diams.

Fig. 214. 20% Sb. × 7 diams.

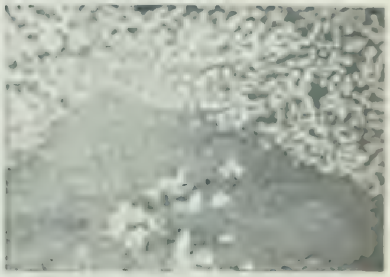


Fig. 215. [illegible] Sb. × 7 diams.

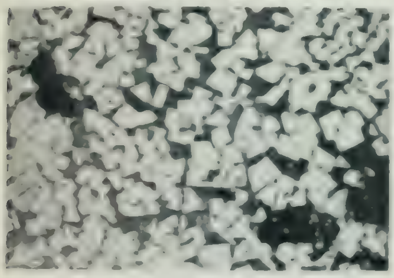


Fig. 216. [illegible] Sb. × 7 diams.

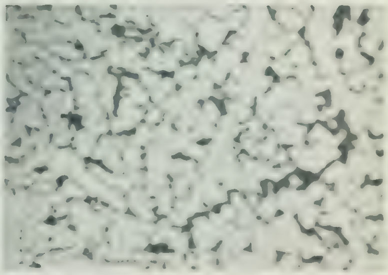


Fig. 217. [illegible] Sb. × 7 diams.

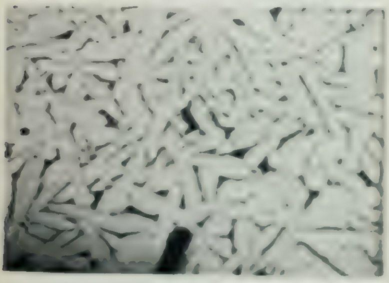
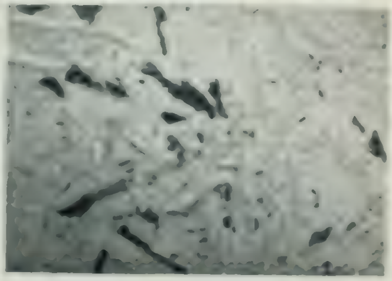


Fig. 218. [illegible] Sb. × 7 diams.



Charles Cochrane

PRESIDENT, 1889.

(Deceased 1898.)

The Institution of Mechanical Engineers.

PROCEEDINGS.

February 1904.

The Fifty-Seventh Annual General Meeting was held at the Institution on Friday, 19th February 1904, at Eight o'clock p.m.; J. Hartley Wicksteed, Esq., President, in the chair.

The Minutes of the previous Meeting were read and confirmed.

The following Annual Report of the Council was then read:—

ANNUAL REPORT OF THE COUNCIL

FOR THE YEAR 1903.

The Council have the pleasure of presenting to the Members the following Report of the progress and work of the Institution during the past year.

During the year the following honours have been conferred upon Members of the Institution. His Majesty the King has created Mr. Charles Sandiford, of Mombasa, a Companion of the Order of the Bath; and Rai Bahadur Ganga Ram, of the Punjaub, a Companion of the Order of the Indian Empire.

The total number in all classes on the roll of the Institution at the end of 1903 was 4,211, as compared with 3,892 at the end of the previous year, showing a net gain of 319, as against the gains of 238, 243, 325, and 402 successively during the four preceding years since the Institution took possession of its new House at the beginning of 1899. During the past year 491 candidates were elected, of whom 47 were formerly Graduates; 1 Member was re-instated, and 3 elections became void, thus making 442 names added to the register. The total deductions have been 123, made up of 46 deceases during 1902 (see Report of 1902), 45 resignations which took effect on 1st January 1903, and 32 removals.

While the rate of progress has not been so high as in 1902, the net increase in the membership of 8¼ per cent must be regarded as very satisfactory.

The following fifty Deceases of Members of the Institution were reported during the year 1903:—

Adams, Charles William (Associate Member),	London.
Astbury, James,	Birmingham.
Bates, Henry,	Salford.
Booth, John William,	Leeds.
Bramwell, Sir Frederick Joseph, Bart., D.C.L., LL.D., F.R.S.,	London.
Brunel, Henry Marc,	London.
Bulmer, John,	Newcastle-on-Tyne.
Cameron, Robert Barr (Associate Member),	Brighton.
Cochrane, William,	Newcastle-on-Tyne.
Cook, Charles,	London.
Davis, Rayner, R.N.,	H.M.S. "Coquette."
Davy, David,	Sheffield.
Downey, Alfred C.,	Middlesbrough.
Dübs, Charles Ralph,	Glasgow.
Foulis, William,	Glasgow.
Fox, Samson,	Leeds.
Hargreaves, John Henry,	Bolton.
Holt, Henry Percy,	London.
Humphrey-Moore, Montague George Alfred (Associate Member),	London.
Humpidge, James Dickerson,	Stroud, Glos.
James, Arthur William,	Calcutta.
James, Victor Augustus Mesham (Associate Member),	London.
Joy, David,	London.
Lea, William Arthur,	Mexico.
Lee, Cuthbert Ridley,	London.
Lloyd, George Braithwaite,	Birmingham.
Lovell, Denis Ralph,	Rio de Janeiro.
Mactear, James, F.R.S.E.,	London.
Marshall, Francis Carr,	Newcastle-on-Tyne.
Moore, Joseph (deceased 1901),	San Francisco.
Nash, Thomas,	Sheffield.
O'Connor, Charles,	Liverpool.
Parker, Thomas,	Gorton.
Pearson, Henry William,	Bristol.
Penn, John, M.P.,	London.
Percy, Cornelius McLeod,	Wigan.
Price, Charles Graham,	Wimbledon.
Rafarel, Frederic William,	Newport, Mon.

Scott, Frederick Whitaker,	Stockport.
Smith, Lionel Lincoln (Associate Member),	Woolwich.
Stanger, William Harry,	London.
Thomson, James McIntyre,	Tarbolton.
Turnbull, John, Jun.,	Glasgow.
Walker, George,	Leeds.
Watson, John Warden,	Leith.
Wheeler, George Cezar (Associate Member),	Cape Town.
Wilson, John Charles Grant,	Manila.
Wilson, William Henry (deceased 1903),	Manchester.
Wrench, John Mervyn,	Bombay.
Wright, William,	London.

Of these, Sir Frederick Bramwell was elected a Member in 1854, Member of Council in 1864, and President in 1874 and 1875; Mr. Francis C. Marshall was elected Member of Council in 1882, and a Vice-President in 1896; and Mr. George B. Lloyd had been a Member from 1854.

The Accounts for the year ended 31 December 1903 are now submitted (see pages 224–227 and 228), having been duly certified by Mr. Robert A. McLean, F.C.A., the Auditor appointed by the Members at the last Annual General Meeting.

The total revenue for the year 1903 was £10,848 15*s.* 4*d.*, while the expenditure was £10,605 2*s.* 3*d.*, leaving a balance of revenue over expenditure of £243 13*s.* 1*d.*, exclusive of Entrance Fees £521 and Life Compositions £50 carried direct to Capital Account. The financial position of the Institution at the end of the year is shown by the balance sheet. The total investments and other assets amount to £70,782 15*s.* 9*d.*, and, deducting therefrom the £25,000 of debentures and the total remaining liabilities, £2,034 9*s.* 5*d.*, the capital of the Institution amounts to £43,748 6*s.* 4*d.*, including the £4,470 L. and N. W. Railway 3 per cent. and the £2,000 Midland Railway 2½ per cent. Debenture Stocks set aside as the nucleus for a Leasehold and Debenture Redemption Fund. The remaining investments consist of £1,945 12*s.* Midland Railway 2½ per cent. Debenture Stock and £1,000 Consols (2½ per cent.). The certificates of the securities have been duly audited by the Finance Committee and the Auditor.

The Sixth Report of the Alloys Research Committee, of which Sir William H. White is the Chairman, has been completed. It deals with the experiments made, under the late Sir William Roberts-Austen's direction, on the Tempering and Annealing of Steel, by Mr. William H. Merrett, who for eight years has been intimately associated, both at the Royal Mint and at the Royal School of Mines, with the work of the Committee, and by others. At the request of the Committee, the Report has been completed by Professor Gowland, to whom, as well as to all who have rendered valuable aid in the investigations, the Council desire to express their great indebtedness.

The four Appendices by Dr. Stansfield, Dr. Reinders, Dr. Campbell, and Mr. Bannister, consist of summaries of fuller Reports, which were handed in by the late Sir William Roberts-Austen shortly before his death.

Notwithstanding that the services of those who have organised the experiments have been gratuitous, the expenditure by the Institution upon this Research, since the formation of the Committee in October 1889, has exceeded £1,800.

The First Report to the Steam-Engine Research Committee, by Professor D. S. Capper, has been received, and will shortly be presented at a Meeting of the Institution. Mr. William H. Maw has been elected Chairman in succession to the late Mr. Bryan Donkin; and the names of Mr. Henry Davey and Captain H. Riall Sankey have been added to the Committee.

Professor Burstall reports that the 100 B.H.P. gas-engine, which has been designed for experimental work in connection with the Gas-Engine Research Committee under the Chairmanship of Dr. Kennedy, is now ready to be tested at the works.

Professor T. Hudson Beare, the Reporter to the Committee on the Value of the Steam Jacket, carried out during the summer and autumn a number of experiments with the experimental jacketed vessel; the results obtained are now being worked out, and further experiments are in progress. New, and it is hoped more satisfactory, valve arrangements for admitting the steam to and exhausting it from the experimental vessels are now being designed by Professor Beare and the Chairman, Mr. Henry Davey.

The Council desire to record their thanks to members and others who have given new books to the Library; also to the donors of various publications of Societies and Public Authorities, and of technical periodicals, of which a list appears on pages 228 to 240.

The Reference Section of the Library, consisting of about 4,000 Books and Pamphlets, has now been re-arranged in subject order upon the shelves according to the Dewey decimal system, which will be found an improvement upon the method previously in use.

The annual Summer Meeting was held in Leeds, and was attended by considerably over 400 members. They were received by the Lord Mayor, who entertained them at the Municipal Buildings. Interesting Papers, contributed by local members and others, were followed by keen discussions.

A local committee, presided over by Mr. Arthur Greenwood, arranged visits to the works of the neighbourhood, including Wakefield, and entertained the members hospitably each day. Mr. E. Kitson Clark and Mr. Christopher W. James acted as Honorary Local Secretaries, and subsequently conducted large parties to Ripon and to York.

Monthly Meetings of the Institution were held throughout the year, with the exception of May to September. These meetings, with the Leeds Meeting, were occupied with the reading and discussion of the following Papers :—

Cutting Angles of Tools for Metal Work, as affecting Speed and Feed; by Mr. H. F. Donaldson.
Hydraulic Experiments on a Plunger Pump; by Professor John Goodman.
A Premium System applied to Engineering Workshops; by Mr. James Rowan.
Address by the President, Mr. J. Hartley Wicksteed.
The Education of Engineers in America, Germany, and Switzerland; by Professor W. E. Dalby.

The Diesel Engine; by Mr. H. Ade Clark.
Notes on High-Speed Tool-Steels; by Mr. Henry H. Suplee.
A new form of Friction Clutch: by Professor H. S. Hele-Shaw, LL.D., F.R.S.
Economy of Fuel in Electric Generating Stations; by Mr. Henry McLaren.
The Newcomen Engine; by Mr. Henry Davey.
Roofing existing Shops while Work is proceeding; by Mr. R. H. Fowler.
Experiments on the Efficiency of Centrifugal Pumps; by Mr. Thomas E. Stanton, D.Sc.
An Inquiry into the working of various Water-Softeners; by Mr. C. E. Stromeyer, and Mr. W. B. Baron.

The Graduates have held monthly Meetings, and have made several Visits to Works, including an excursion to Southampton and Eastleigh. The attendance has been satisfactory, and each Meeting was presided over by a Member of Council or other prominent Member of the Institution. The following Papers were read and discussed:—

Some Notes on the Locomotive; by Mr. James McGregor.
The Construction, Lighting, and Ventilation of Cotton Mills; by Mr. Frank Wilkinson.
Automatic Couplers; by Mr. F. C. Hibberd.
Deep-Well Pumping Machinery; by Mr. W. P. Gauvain.
The Deterioration of Steam Boilers: by Mr. H. M. Warner.
Grabs; by Mr. F. W. Howl.

The Papers by Mr. Gauvain and Mr. Hibberd have gained prizes from the Council, and will be published in the Proceedings.*

At the February Meeting of the Graduates, Dr. R. T. Glazebrook, F.R.S., delivered a lecture on "The National Physical Laboratory and its Relation to Engineering," illustrated by lantern slides.

The Engineering Standards Committee have held frequent meetings during the year, and have published four Reports relating to Standard sizes for Rolled Sections and Beams. The Council have handed over to this Committee the further investigation relating to the Standardization of Pipe Flanges, which subject is now being dealt with by a Sub-Committee of the Engineering Standards Committee, with Mr. William H. Maw as Chairman.

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* Proceedings 1903, Part 4, pages 887 and 899.

A cordial invitation from the American Society of Mechanical Engineers to hold a joint meeting in Chicago, with a view to subsequently visiting the St. Louis Exhibition, has been accepted by the Council on behalf of the Members.

The result of the Ballot for the election of President, two Vice-Presidents, and seven Members of Council, to fill the vacancies caused by retirement, will be announced at the Annual General Meeting.

Dr. ACCOUNT OF EXPENDITURE AND REVENUE

Expenditure.

	£	*s.*	*d.*	£	*s.*	*d.*
To Expenses of Maintenance and Management—						
Salaries and Wages	2,717	19	9			
Postages, Telegrams, and Telephone	585	4	7			
Heating, Lighting, and Power	162	2	2			
Fittings and Repairs	100	18	1			
Housekeeping	140	15	9			
Incidental Expenses	61	17	3			
				3,768	17	7
,, Printing, Stationery, and Binding—						
Printing and Engraving Proceedings	1,588	1	0			
Stationery and General Printing	614	12	1			
Binding	61	16	5			
				2,264	9	6
,, Rent, Rates, Taxes, &c.—						
Ground Rent	875	17	2			
Rates and Taxes	921	17	8			
Insurance	33	4	0			
				1,830	18	10
,, Meeting Expenses—						
Printing	329	4	1			
Reporting	54	12	8			
Travelling and Incidental Expenses	129	12	7			
				513	9	4
,, Conversazione				180	10	2
,, Dinner Expenses				47	0	2
,, Graduates' Prizes				9	6	6
,, Books purchased				15	13	7
,, Law Charges				8	8	0
,, Engineering Standards Committee				100	0	0
,, Expenses in connection with Research Committees				92	2	6
,, Re-wiring Institution Building, and additional Fittings				707	18	7
,, Depreciation on Furniture and Fittings				63	5	1
,, Debenture Interest				1,000	0	0
,, Interest on Bank overdraft				3	2	5
Total Expenditure				10,605	2	3
,, Balance, being excess of Revenue over Expenditure (exclusive of Entrance Fees £523, and Life Compositions £50, carried to Capital Account), carried to Balance Sheet				243	13	1
				£10,848	15	4

FOR THE YEAR ENDED 31st DECEMBER 1903. *Cr.*

Revenue.

	£ s. d.	£ s. d.
By Subscriptions for 1903		10,413 10 0
" Estimated value of Subscriptions in arrear (*being equal to the amount received in 1903*)	127 10 0	
Add difference between estimated value in last account and actual receipts in 1903	71 10 0	199 0 0
" Interest, &c.—		
From Investments and Bank	116 2 6	
Income Tax refunded	15 15 5	131 17 11
" Reports of Proceedings—		
Extra Copies sold		104 2 5
" Debenture Transfer Fees		0 5 0
		£10,848 15 4

Dr. **BALANCE SHEET**

				£	s.	d.
To Debentures—						
250 *of* £100 *each at* 4%, *redeemable in* 1917, *or at par at any date after* 1st *Jan.* 1908, *on six months' notice to holder*				25,000	0	0
„ Sundry Creditors—	£	s.	d.			
Accounts owing at 31*st Dec.* 1903 (*since paid*) .	1,765	3	2			
Unclaimed Debenture Interest (*coupons not presented*)	116	6	3			
				1,881	9	5
„ Subscriptions paid in advance				153	0	0
„ Capital of the Institution :—						
Balance at 31*st Dec.* 1902	39,474	6	2			
Deduct—						
Further amount set aside for Redemption of Debentures and Institution's Leasehold Property, being cost of £2,000 *Midland Ry.* 2½% *Debenture Stock*	1,306	6	7			
	38,167	19	7			
Add :—						
Excess of Revenue over Expenditure for the year ended 31*st Dec.* 1903 . .	243	13	1			
Amount received from Life Compositions during 1903	50	0	0			
Amount received from Entrance Fees during 1903	523	0	0			
				38,984	12	8
Amount invested in £4,470 *London and North Western Ry.* 3% *Debenture Stock, and* £2,000 *Midland Ry.* 2½% *Debenture Stock, with interest thereon, set aside for Redemption of Debentures and Institution's Leasehold Property, see contra*				4,763	13	8
(*The Market Value of these investments and interest at* 31*st Dec.* 1903 *was about* £5,896.)						
				£70,782	15	9

Signed by the following members of the Finance Committee :—

E. B. ELLINGTON,
B. BAKER,
HENRY CHAPMAN,
H. GRAHAM HARRIS.

AT 31st DECEMBER 1903. *Cr.*

	£	s.	d.	£	s.	d.		£	s.	d.
By Cash—										
In Union of London and Smiths Bank	249	17	7							
Less cheque outstanding	11	12	6							
				238	5	1				
In the Secretary's hands				23	12	9				
								261	17	10
„ Investments							*Cost*	2,401	5	7
£ 1,945 12s. *Midland Ry. 2½% Debenture Stock.* 1,000 2¾% *Consols.* *The Market Value of these investments at 31st Dec. 1903 was about £2,397 11s. 4d.*										
„ Investment of Amount set aside for Redemption of Debentures and Institution's Leasehold Property, *see contra*								4,763	13	8
£4,470 London and North Western Ry. 3% Debenture Stock, and £2,000 Midland Ry. 2½% Debenture Stock, cost £4,699 19s. 2d. with £63 14s. 6d. balance of interest thereon to be invested. *These investments with their accumulating interest are set aside for the above purpose.*										
„ Subscriptions in Arrear, *estimated value (being equal to the amount received during* 1903)								427	13	0
„ Furniture and Fittings (*less depreciation*)								1,201	16	7
„ Books in Library, Drawings, Engravings, Models, Specimens, and Sculpture (*estimate of* 1893)								1,340	0	0
„ Amount in Union of London and Smiths Bank to meet unclaimed Debenture Interest (*coupons not presented*)								116	6	3
„ Proceedings—stock of back numbers, *not valued.*										
„ Institution House							*Cost*	60,270	2	10
								£70,782	15	9

I certify that all my requirements as Auditor have been complied with, and I report to the Members that I have audited the above Balance Sheet, dated the 31st December 1903, and in my opinion such Balance Sheet is properly drawn up and exhibits a true and correct view of the state of the affairs of the Institution as shown by its Books.

ROBT. A. McLEAN, F.C.A.,
Auditor,
1 Queen Victoria Street, London, E.C.

14th January 1904.

WILLANS PREMIUM FUND.

Investment £159 8*s.* 5*d.* of India 3% Stock . . . . cost £165 5*s.* 0*d.*

Dr.	£	*s.*	*d.*		*Cr.* £	*s.*	*d.*
To Balance, held in trust .	14	6	0	By Interest, 1901 . . .	4	15	4
(*To be awarded by the*				,, ,, 1902 . . .	4	15	4
Institution of Electrical				,, ,, 1903 . . .	4	15	4
Engineers in 1904.)							
	£14	6	0		£14	6	0

Audited, certified, and signed by the names on pages 226–227.

(For the Declaration of Trust, *see* Proceedings 1901, page 16.)

LIST OF DONATIONS TO THE LIBRARY.

BOOKS (*in order received*).

Designing and Equipment of Blast Furnaces, by John L. Stevenson; from the author.

Briquettes and Patent Fuel, by Philip R. Björling; from the publishers.

Well-Boring for Water, Brine, and Oil, by C. Isler; from Mr. Michael M. Brophy.

Emery-Grinding Machinery; Machines and Tools employed in the working of Sheet Metals; from the author, Mr. R. B. Hodgson.

Descriptive volume of the Opening of the Building of the Chamber of Commerce of the State of New York; from Mr. Morris K. Jesup.

Sub-Mechanics of the Universe, by Osborne Reynolds; from the author.

Raccolta Voltiana; from Museo Civico, Como (per The Institution of Electrical Engineers).

Internal Wiring of Buildings, by H. M. Leaf; from the publishers.

Resistance and Power of Steamships, by W. H. Atherton and A. L. Mellanby: from Mr. W. H. Atherton.

Radiant Energy, a Working Power in the Mechanism of the Universe, by R. W. O. Kestel: from the author.

The following from Mr. Frederick Colyer:—Breweries and Maltings: their Arrangement, Construction, Machinery, and Plant, by G. Scamell, 2nd ed. revised by Frederick Colyer. Gas Works: their Arrangement, Construction, Plant, and Machinery, by Frederick Colyer. Hydraulic, Steam, and Hand-Power Lifting and Pressing Machinery, by Frederick Colyer. Public Institutions: their Engineering, Sanitary, and other Appliances, by Frederick Colyer. Pumps and Pumping Machinery, 2 vols., 2nd ed., by Frederick Colyer. Treatise on the Modern Sanitary Appliances, by Frederick Colyer. Treatise on Water Supply, Drainage, etc., by Frederick Colyer. Treatise on the Working and Management of Steam Boilers and Engines, by Frederick Colyer.

Gemeinfassliche Darstellung des Eisenhuttenwesens; Jahrbuch fur das Eisenhuttenwesen, Jahr. II: from the publisher.

Mechanical Refrigeration, by Hal Williams: from the author.

Bonus Tables, for calculating Wages on the Bonus or Premium Systems, by H. A. Golding: from the publishers.

Locomotives au début du XXe Siècle, by Edouard Sauvage: from the author.

Water Supply, by R. E. Middleton: from the author.

Electric Lighting and Power Distribution, Vol. II, by W. P. Maycock; from the author.

Manual of Practical Mathematics, by Frank Castle: from the author.

Reed's Marine Stokers' Guide, by Vulcan: from the author.

The following from Mr. W. J. Weightman:—Text-Book of Electrochemistry, by Svante Arrhenius. Lehrbuch der Elektrochemie, by Dr Max le Blanc. Elements of Metallurgy, by J. A. Phillips. Richter's Inorganic Chemistry (5th ed. translated by Edgar F. Smith). Select Methods in Chemical Analysis, by William Crookes. Electrolytic Separation of Metals, by G. Gore. Secondary Batteries: their Theory, Construction and Use, by E. J. Wade. Transactions of the American Electro-chemical Society, Vols. I and II. Electric Smelting and Refining, by Dr W. Borchers (2nd ed. translated by W. G. McMillan).

Friction and its Reduction, by G. H. Wheeler: from the publishers.

Electric Traction, by J. H. Rider; from the author.

Fragments from Continental Journeyings, by A. R. Sennett; from the author.

The Dynamo, by C. C. Hawkins and F. Wallis: from the publishers.

Technik und Praxis wichtigsten Physikalischen Grossen, by Olof Linders; from the author.

OFFICIAL PUBLICATIONS.

The following from the Government of Canada:—Report of the Commissioner of Public Works for the province of Ontario for the years ending 31 Dec. 1901 and 31 Dec. 1902; Statistical Year-book, 1902; Canadian Trade Index, 1901.

Annual Report of the Columbian Minister of Mines for the years ending 31 Dec. 1901 and 31 Dec. 1902; from the Minister.

The following from the Government of India:—Report of the Chief Inspector of Mines in India for the years ended 31 Dec. 1901 and 31 Dec. 1902; Technical Section Papers.

The following Official Publications from the Government of New South Wales:—Annual Report of the Department of Mines, 1902; Report of the Department of Public Works for the year ended 30 June 1902; Annual Report of the Railway Commissioners for the years ended 30 June 1902 and 30 June 1903; The Seven Colonies of Australasia, 1901–1902, by T. A. Coghlan; Report on Artesian Boring and Irrigation in America, by J. W. Boultbee; Moore's Almanac, 1903.

The following Official Publication from the Government of Queensland:—Brisbane Board of Waterworks, Report for the year ended 31 Dec. 1901.

The following from the Government of the United States of America:—Annual Report of the Chief of Ordnance, 1902; Notes on the Construction of Ordnance; Tests of Metals, 1901 and 1902; Annual Report of the Chief of the Bureau of Steam Engineering, 1903.

The following from the U.S. Geological Survey:—Twenty-Second Annual Report, Parts I, II, III, and IV, 1900–1901; Twenty-Third Annual Report, 1901–1902; Monographs, XLII and XLIII; Mineral Resources of the United States, 1901; Bulletins, 191, 195–207; Professional Papers, I to VIII; Water Supply and Irrigation Papers, Nos. 65–79.

The following Official Publications from the Government of Western Australia:—Supplement to Government Gazette of Western Australia; Report of the Department of Mines, 1902; Report on the Working of the Government Railways and the Roebourne-Cossack Tramway, 30 June 1902; Statistical Register for the year 1901; History of the Coolgardie Water Scheme.

PAMPHLETS, &c.

Memoir of James Watt, 1736-1819; Geometrical Method of proving the contents of a Pyramid and of a Cone; from Sir Frederick Bramwell, Bart., D.C.L., LL.D., F.R.S.

Stresses Developed in Beams Loaded Transversely, by Professor Henry T. Bovey, LL.D., F.R.S.; from the author.

Note sur un Carburateur a Reglage Automatique pour Moteurs à Explosions, by M. Krebs; from Mr. Henry Chapman.

Imperial Telegraphic Communication and the "All-British" Pacific Cable, by Charles Bright, F.R.S.E.; from the author.

Untersuchungen am Gasmotor, by Eugen Meyer; from the author.

Winding Plants for Great Depths, by H. C. Behr; from the author.

Presidential Address to the Australasian Association for the Advancement of Science, by F. W. Hutton; from the author.

History of the Belvoir Castle Edge-Rail Way; Railway Collection at the Leicester Museum; History of the North-Western Railway; History of the Preston and Walton Summit Plate-way; from the author, Mr. C. E. Stretton.

Lecture on Producer-Gas, and its application to Industry, by H. A. Humphrey; from the author.

Improved Mode of Procedure for the Grant of Letters Patent, by G. G. M. Hardingham; from the author.

Le Navire pour Passagers, by C. Ture; from the publishers.

Notes on the Census Report (1901) for the County of Lancaster, by T. A. Welton; from the Manchester Statistical Society.

Restoration of the Ancient Irrigation Works on the Tigris or the Re-Creation of Chaldea, by Sir William Willcocks.

Presidential Address to the Royal Philosophical Society of Glasgow, by Professor Archibald Barr; from the author.

The Metric System, by F. A. Halsey; Report of Committee appointed to discuss the Arguments in favour of and against the Metric System; from the American Society of Mechanical Engineers.

British v. American Patent Law Practice and Engineering Invention; Effect of Flue Dust upon the Thermal Efficiency of Hot-Blast Stoves; Joseph Aspdin: Inventor of Portland Cement; from the author, Mr. B. H. Thwaite.

Modern Machinery for Excavating and Dredging; Stewart River Gold Dredge; from the author, Mr. A. W. Robinson.

Value of Wind-Mills in India, by Professor Alfred Chatterton; from the author.

Les Turbines a Vapeur, et specialement les Turbines Parsons, by M. Hart; from Association Technique Maritime.

Notes on Internal Flow in Centrifugal Pumps, Part II: a Study of the Theory of the Runner, by J. A. Smith; from the author.

L'Effort de Traction: Expériences en Angleterre, by Professor H. S. Hele-Shaw, LL.D., F.R.S.; from the author.

Vorrichtungen zur zeitweiligen Erhöhung des Triebraddruckes bei Lokomotiven als Mittel zur Lösung des Anfahrproblems, by K. Keller; from the author.

Oil Tempering of Mild Steel Forgings, by T. Bunt; from the author.

Historical Sketch of the Experimental Determination of the Resistance of the Air to the Motion of Projectiles, by Francis Bashforth; from the author.

Elan Valley Waterworks; Premium System of Paying Wages; from Mr. Edgar Worthington.

Bakerian Lecture—On the Constitution of the Copper-Tin Series of Alloys, by C. T. Heycock, F.R.S., and F. H. Neville, F.R.S.; from the authors.

Hearing of Actions, by H. E. Garle; from the author.

Notes on Material, Construction, and Design of Land Boilers, by E. G. Hiller; from the author.

Cylinder Oil and Cylinder Lubrication, by H. M. Wells; from the author.

Ankylostomiasis: its cause, treatment, and prevention; from the publishers.

Comparison of certain Physical Properties of Nickel Steel and Carbon Steel for Bridge and Structural Purposes, by A. L. Colby; from the author.

Electricity for Small Hospitals, by W. N. Twelvetrees; from the author.

Cathodic Reduction (2 copies), by A. T. Weightman; from the author.

Design of Plate Girders; Strengths of the Materials of Construction; from the author, Professor W. E. Lilly.

The Science of the Engineering Workshop, by William Taylor; from the author.

Design and Manufacture of Milling Cutters, by S. N. Brayshaw; from the author.

Statically Indeterminate Structures, by I. Kreuger; from the author.

Der Beschleunigungsdruck der Schub-stange; Der Ungleichförmigkeitsgrad von Vier-takt-motoren mit Aussetzer-reglung, by Professor Dr. R. Mollier; from the author.

The Inch, the Metre, and the Metric System; from Mr. Thomas Parker.

Report on the Abatement of Smoke Nuisance in Calcutta, by Frederick Grover; from the author.

The following from the Engineering Standards Committee:—British Standard Sections, No. 1, Angles, &c.; No. 2, Tramway Rails and Fish Plates; No. 3, Report on the Influence of Gauge Length and Section of Test Bar upon the Percentage of Elongation, by Professor W. C. Unwin; No. 4, Beams.

Rede zum Geburtsfeste Seiner Majestät des Kaisers und Königs Wilhelm II. in der Halle der Königlichen Technischen Hochschule zu Berlin, 26 Januar 1903; Dissertation zur Erlangung der Würde eines Doktor-Ingenieurs, by Walter Reichel; Reibungsbahnen und Bahnen gemischten Systems, by Otto Blum; Die Verwendung von Druckluft bei elektrisch betriebenen

Halbzeugen, by Franz Jordan; Über die Vergrösserung der Handelsdampfer mit Rücksicht auf ihre Rentabilität, by Clarence B. Schultz; from the Rector, Berlin Königlichen Technischen Hochschule.

Report of the Hydraulic Engineer on the Water Supply of Queensland, 1901; from Mr. John B. Henderson.

List of Chinese Lighthouses, Light-Vessels, Buoys, and Beacons, 1904; from the Inspector-General of Chinese Customs.

Board of Trade Reports on Boiler Explosions; Comparison and Verification of Measures of Length for Geodetic, Survey, and Engineering Purposes; from the Board of Trade.

Classified Lists and Distribution Returns of Establishment, Indian Public Works Department, to 31 December 1902 and 30 June 1903; from the Registrar.

Incorporated Accountants' Year Book, 1903–4; from the Society of Accountants and Auditors.

Universal Directory of Railway Officials, 1903; from the publishers.

Donaldson's Engineers' Annual, 1903; from Mr. P. R. Owens.

The following from the Patent Office:—Abridgments of Specifications of Patents for Inventions, 1897–1900:—Classes 11, 43–46, 48–135, 137–146; 1867–76:—Classes 4, 7, 8, 12, 17, 23, 27, 29, 32–34, 41, 54, 57, 59, 63–67, 71; Patent Office Library Catalogue, Vol. 1, 1898 (Authors), Vol. 2, 1883 (Subjects); Guide to the Search Department of the Patent Office Library, with Appendices (2nd ed.); Subject List of works on General Science, Physics, Sound, Music, Light, Microscopy, and Philosophical Instruments; Ditto of works on Architecture and Building Construction; Ditto of works on the Mineral Industries and Allied Sciences; Illustrated Official Journal (Patents).

CALENDARS, ETC.

Calendars 1903–1904 from the following Colleges:—Royal Technical High School, Berlin; University of Birmingham, (Calendar and Journal); Bradford Municipal Technical College; University College, Bristol; Glasgow and West of Scotland Technical College, (Calendar and Report); Yorkshire College, Leeds, (Calendar and Report); City of London College; King's College, London; South Western Polytechnic, London; University College, London; McGill College and University, Montreal; Redruth School of Mines; University College, Sheffield.

University College of South Wales and Monmouthshire, Cardiff, Calendar 1902–1903; from the College.

Report to the Governors of the City and Guilds of London Institute, April 1903; from the Institute.

Crystal Palace Engineering School Magazine; from Mr J. W. Wilson.

South Australia School of Mines and Industries and Technological Museum, Annual Report 1902; from the School.

Royal Technical High School, Munich, Report 1901–1902, Calendar 1902–1903; from the School.

The following from California University, U.S.America:—Register, 1901–1902, 1902–1903; Secretary's Annual Report, 1901; Chronicle, Vol. 5, Nos. 1–4, Vol. 6, No. 1; Bulletin, Vol. 3, Nos. 1–12; President's Biennial Report, 1900–1902.

Michigan College of Mines, Year-book 1902–1903; from the College.

Cornell University, New York, Register 1902–1903; from the University.

CATALOGUES.

Standard Methods for the Testing and Analysis of Cements; from Messrs. G. and T. Earle.

E. P. S. Batteries, 1903; from the Electrical Power Storage Co.

Hydraulic Lifting, Pressing and Pumping Machinery; from Messrs. C. and A. Musker.

Engraving Machinery; from Messrs. Taylor, Taylor and Hobson.

Engineers' Stores, Machinery, Tools, Lubricating Oils, &c.; from Messrs. W. H. Willcox and Co.

Boiler Mountings, &c.; from Messrs. James Baldwin and Co.

Conveying, Screening and Crushing Plants; from Messrs. Graham, Morton and Co.

Rolled Steel Sections; from Messrs. Rogers, Twentyman and Co.

Boiler Mountings; from Messrs. Fletcher Brothers.

Appleby's Handbook of Machinery.—Section 3, Pumping Machinery; Section 5, Contractors' Plant, Railway Materials, Notes, Tables, etc.; from Messrs. Jessop and Appleby Brothers.

De Laval Patent Steam Turbine Machinery; from Messrs. Greenwood and Batley.

Spons' Engineers' Price Book, 1903–4; from Messrs. E. and F. N. Spon.

Photographic Machinery; from Messrs. N. L. Scott and Co.

Surveying and Drawing Instruments (G); from Messrs. W. F. Stanley and Co.

Steam and Electric Cranes; from Messrs. J. H. Wilson and Co.

Cut Gearing and Machine Cut Wheels; from Messrs. David Brown and Sons.

Baldwin Locomotive Works, Records of Recent Construction, Nos. 39–44, 1903; from the Company.

PHOTOGRAPH.

Photograph of 20,000 I.H.P. Engines of the twin-screw Italian warship, "Re Umberto," from Mrs. Joy.

MAP.

Map of Peru, from Don E. Larrabure y Unanue.

The following PUBLICATIONS from the respective Societies and authorities:—

BRITISH ISLES.

Bradford Libraries, Art Gallery, and Museums Committee; Thirty-third Annual Report.
British Association for the Advancement of Science; Report.
British Fire Prevention Committee.
Chemistry of Great Britain and Ireland, Institute of; Proceedings, and List of Fellows 1903-4.
Civil Engineers, The Institution of; Proceedings.
Civil and Mechanical Engineers' Society; Transactions.
Cleveland Institution of Engineers, Middlesbrough; Proceedings.
Cold Storage and Ice Association; Proceedings.
Electrical Engineers, Institution of; Journal.
Engine, Boiler, and Employers' Liability Insurance Company, Manchester Report (from Mr. Michael Longridge).
Engineers and Shipbuilders in Scotland, Institution of, Glasgow; Transactions.
Incorporated Gas Institute; Transactions.
Ipswich Engineering Society; Transactions.
Iron and Steel Institute; Journal.
Junior Engineers, Institution of; Transactions.
Literary and Philosophical Society of Manchester; Memoirs and Proceedings.
Liverpool Engineering Society; Transactions.
Liverpool Public Libraries, Museums, and Art Gallery; Fiftieth Annual Report.
Manchester Geological and Mining Society; Transactions.
Manchester Steam Users' Association; Report.
Marine Engineers, Institute of; Transactions.
Mining Engineers, Institution of, Newcastle-on-Tyne; Transactions.
National Physical Laboratory; Reports 1901 and 1902.
Naval Architects, Institution of; Transactions.

North of England Institute of Mining and Mechanical Engineers, Newcastle-on-Tyne; Transactions.

North-East Coast Institution of Engineers and Shipbuilders, Newcastle-on-Tyne; Transactions.

Philosophical Society of Glasgow; Proceedings.

Physical Society of London; Proceedings.

Radcliffe Library, Oxford; Catalogue of Additions during 1902.

Royal Agricultural Society of England; Journal.

Royal Cornwall Polytechnic Society, Falmouth; Report.

Royal Dublin Society; Transactions and Proceedings.

Royal Engineers' Institute, Chatham; Professional Papers.

Royal Institute of British Architects; Journal.

Royal Institution of Great Britain; Proceedings.

Royal Irish Academy, Dublin; Transactions and Proceedings.

Royal Scottish Society of Arts, Edinburgh; Transactions.

Royal Society of Edinburgh; Proceedings.

Royal Society of London; Philosophical Transactions (A), Proceedings, and Year-Book 1903.

Royal United Service Institution; Journal.

Science Abstracts—Physics and Electrical Engineering.

Society of Arts; Journal.

Society of Chemical Industry; Journal.

Society of Engineers; Transactions.

South Wales Institute of Engineers, Cardiff; Proceedings.

Staffordshire Iron and Steel Institute, Dudley; Proceedings.

Surveyors' Institution; Transactions and Professional Notes.

Waterworks Engineers, British Association of; Transactions.

West of Scotland Iron and Steel Institute, Glasgow; Journal.

Africa.

South African Association of Engineers, Johannesburg; Proceedings.

Argentine Republic.

Engineers of River Plate, Institution of, Buenos Aires; Journal.

Austria.

Zeitschrift des Oesterreichischen Ingenieur- und Architekten-Vereines, Vienna.

Zprávy spolku Architektův a Inženýrů v království českém, Prague.

Belgium.

Académie Royale de Belgique, Brussels; Bulletin.
Association des Ingénieurs sortis des Écoles spéciales de Gand; Annales.
International Railway Congress (English edition), Brussels; Bulletin.

Canada.

Canadian Society of Civil Engineers, Montreal; Transactions.
Nova Scotian Institute of Science; Proceedings and Transactions.

France.

Académie des Sciences, Paris; Comptes Rendus des Séances.
Annales des Mines, Paris.
Association Technique Maritime, Paris; Bulletin.
Associations de Propriétaires d'Appareils à Vapeur, Paris; Compte Rendu des Séances.
Conservatoire des Arts et Métiers, Paris; Annales.
Ponts et Chaussées, Paris; Annales.
Revue Maritime, Paris.
Société Scientifique Industrielle, Marseilles; Bulletin.
Société d'Encouragement pour l'Industrie Nationale, Paris; Bulletin.
Société Industrielle de Mulhouse; Bulletin.
Société Industrielle du Nord de la France, Lille; Bulletin.
Société Industrielle de Rouen; Bulletin.
Société Industrielle de St. Quentin et de l'Aisne, St. Quentin; Bulletin.
Société des Ingénieurs Civils de France, Paris; Mémoires.

Germany.

Zeitschrift für Architektur und Ingenieurwesen, Hannover.
Zeitschrift des Bayerischen Dampfkessel-Revisions-Vereins, Munich.
Zeitschrift des Vereines deutscher Ingenieure, Berlin.

Holland.

Tijdschrift van het Koninklijk Instituut van Ingenieurs, 's Gravenhage.

India.

Asiatic Society of Bengal, Calcutta; Proceedings and Journal.

Italy.

Associazione fra gli Utenti di Caldaie a Vapore nelle Provincie Napolitane Rapporto dell' Ingegnere Direttore.
Associazione Elettrotecnica Italiana, Rome; Atti.
Società degli Ingegneri e degli Architetti Italiani, Rome; Annali.

Japan.

Japan Society of Mechanical Engineers, Tokyo; Journal.

New South Wales.

Royal Society of New South Wales, Sydney; Journal and Proceedings.

Norway.

Teknisk Ugeblad, Christiania.

Sweden.

Geological Institution of the University of Upsala; Bulletin.
Svenska Teknologföreningen, Stockholm.

United States.

American Academy of Arts and Sciences, Boston; Proceedings.
American Institute of Mining Engineers, New York; Transactions.
American Philosophical Society, Philadelphia; Transactions and Proceedings.
American Society of Civil Engineers, New York; Transactions and Proceedings.
Association of Engineering Societies, Philadelphia; Journal.
Franklin Institute, Philadelphia; Journal.
John Crerar Library, Chicago; Eighth Annual Report.
Master Car-Builders' Association, Chicago; Proceedings.
School of Mines Quarterly, Columbia College, New York.
Smithsonian Institution, Washington; Annual Report.
United States Artillery, Fort Monroe; Journal.
United States Naval Institute, Annapolis; Proceedings.
United States Patent Office Gazette, Washington.
Western Society of Engineers, Chicago; Journal.

Victoria.

Australasian Institute of Mining Engineers, Melbourne; Transactions.

The following PERIODICALS from the several Editors :—

BRITISH ISLES.

Arms and Explosives.
The Autocar.
Automobile Club Journal.
The Automotor Journal.
Board of Trade Journal (from Mr. Henry Chapman).
The British Architect.
The British Empire Review (from Mr Henry Chapman).
British Refrigeration.
The Builder.
Camera Club Journal.
The Car.
Cassier's Magazine.
The Chamber of Commerce Journal (from Mr. Henry Chapman).
Cold Storage and Ice Trades Review.
The Colliery Guardian.
The Contract Journal.
The Cyclist.
The Electrical Engineer.
The Electrical Review.
The Electrical Times.
The Electrician.
The Electro-Chemist and Metallurgist.
The Engineer.
The Engineer and Iron Trades' Advertiser.
Engineering.
The Engineering Magazine.
Engineering Times.
Engineers' Gazette.
The Export Review.
Feilden's Magazine.
The Fireman.
The Fishing Gazette.
The Foundry Trade Journal.
The Journal of Gas Lighting.
The Gas World (and Yearbook 1904).
The Hardware Trade Journal.
Ice and Cold Storage.
Illustrated Scientific News.
The Iron and Coal Trades Review.
Iron Trade Circular, Ryland's.
The Ironmonger.
Locomotive Magazine.
London Technical Education Gazette.
London University Gazette.
The Machinery Market.
The Marine Engineer.
The Mariner.
The Mechanical Engineer.
The Mechanical World.
Midland Counties Herald.
The Mining Journal.
Model Engineer and Amateur Electrician.
Motor Car Journal.
Page's Magazine.
Petroleum.
The Plumber and Decorator.
The Practical Engineer.
The Public Health Engineer.
The Publishers' Circular.
The Quarry.
The Railway Engineer.
The Refrigerating Engineer.
The Shipping World.
The Steamship.
The Surveyor.
The Textile Recorder.
Traction and Transmission.
The Tramway and Railway World.
Transport.
Water.
The Woodworker.

Belgium.

Revue Universelle des Mines.

France.

L'Industrie.
Revue générale des Chemins de fer.
Revue Industrielle (from Mr. Henry Chapman).

Germany.

Glaser's Annalen.
Stahl und Eisen.

Holland.

De Ingenieur.

India.

The Indian and Eastern Engineer.
Railways.
Indian Textile Journal (English edition).

Italy.

Giornale del Genio Civile.

Spain.

El Ingeniero Español (London edition).

United States.

American Machinist.
American Manufacturer.
The Automobile.
Electrical Review.
Electrical World and Engineer.
Electricity.
The Engineer.
The Engineering and Mining Journal.
Engineering News.
The Engineering Record.
The Iron Age (from Mr. W. H. Maw).
Marine Engineering.
Marine Review.
The Railway and Engineering Review.
Railway Master Mechanic.

The Museum has received six pieces of Rail with Sleepers from Mr. Clement E. Stretton.

The President formally moved the adoption of the Annual Report, which was unanimously agreed to.

The President next presented to Mr. F. C. Hibbard the Prize awarded by the Council for his Paper on "Automatic Couplers."

He announced that Mr. W. P. Gauvain, who had also been awarded a Prize by the Council for his Paper on "Deep-Well Pumping Machinery," was unable to be present, and his prize would therefore be forwarded to him.

The President announced that the Ballot Lists for the election of Officers for the present year had been opened by a Committee of the Council, and that the following were found to be duly elected:—

PRESIDENT.

J. Hartley Wicksteed,	Leeds.

VICE-PRESIDENTS.

Edward B. Ellington,	London.
T. Hurry Riches,	Cardiff.

MEMBERS OF COUNCIL.

Sir Benjamin Baker, K.C.B., K.C.M.G., LL.D., D.Sc., F.R.S.,	London.
Sir J. Wolfe Barry, K.C.B., LL.D., F.R.S.,	London.
Henry Chapman,	London.
Edward Hopkinson, D.Sc.,	Manchester.
Henry A. Ivatt,	Doncaster.
Henry D. Marshall,	Gainsborough.
Sir John I. Thornycroft, LL.D., F.R.S.,	London.

The Council for the present year is therefore as follows:—

PRESIDENT.

J. Hartley Wicksteed,	Leeds.

PAST-PRESIDENTS.

Sir Lowthian Bell, Bart., LL.D., F.R.S.,	Northallerton.
Sir Edward H. Carbutt, Bart.,	London.
Samuel Waite Johnson,	Nottingham.
Professor Alex. B. W. Kennedy, LL.D., F.R.S.,	London.
William H. Maw,	London.
E. Windsor Richards,	Caerleon.
Percy G. B. Westmacott,	Ascot.
Sir William H. White, K.C.B., LL.D., D.Sc., F.R.S.,	London.

VICE-PRESIDENTS.

John A. F. Aspinall,	Manchester.
Edward B. Ellington,	London.
Arthur Keen,	Birmingham.
Edward P. Martin,	Dowlais.
T. Hurry Riches,	Cardiff.
A. Tannett-Walker,	Leeds.

MEMBERS OF COUNCIL.

Sir Benjamin Baker, K.C.B., K.C.M.G., LL.D., D.Sc., F.R.S.,	London.
Sir J. Wolfe Barry, K.C.B., LL.D., F.R.S.,	London.
Henry Chapman,	London.
Henry Davey,	London.
William Dean,	Folkestone.
H. Graham Harris,	London.
Edward Hopkinson, D.Sc.,	Manchester.
Henry A. Ivatt,	Doncaster.
Henry Lea,	Birmingham.
Sir William T. Lewis, Bart.,	Aberdare.
Michael Longridge,	Manchester.

James Mansergh, F.R.S.,	London.
Henry D. Marshall,	Gainsborough.
The Rt. Hon. **William J. Pirrie**, LL.D.,	Belfast.
Sir **Thomas Richardson**,	Hartlepool.
John F. Robinson,	London.
Mark H. Robinson,	Rugby.
John W. Spencer,	Newcastle-on-Tyne.
Sir **John I. Thornycroft**, LL.D., F.R.S.,	London.
John Tweedy,	Newcastle-on-Tyne.
Henry H. West,	Liverpool.

The **President** reminded the Members that at the present Meeting the appointment had to be made of an auditor for the current year.

Mr. **W. H. Allen** moved: "That Mr. Robert A. McLean, F.C.A., 1 Queen Victoria Street, London, be re-appointed to audit the accounts of the Institution for the present year, at the same remuneration as last year, namely, twenty-five guineas."

Mr. **Druitt Halpin** seconded the motion, which was carried unanimously.

The Discussion on the Sixth Report to the Alloys Research Committee on the "Heat Treatment of Steel" was resumed and concluded (page 139).

The following Paper was then read and discussed:—

"The Motion of Gases in Pipes, and the use of Gauges to determine the Delivery"; by Mr. **Richard Threlfall**, F.R.S., of Birmingham.

The Meeting terminated at Ten o'clock. The attendance was 102 Members and 64 Visitors.

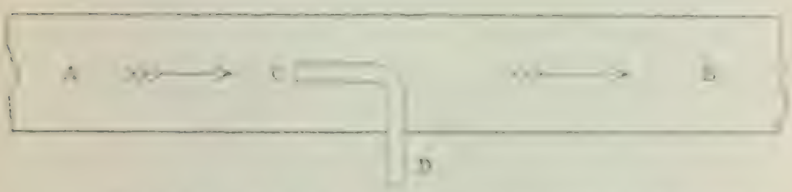
THE MOTION OF GASES IN PIPES, AND THE USE OF GAUGES TO DETERMINE THE DELIVERY.

By Mr. RICHARD THRELFALL, F.R.S., of Birmingham.

It is necessary to give a preliminary statement* of the hydrodynamic principles involved, in order that what follows may be free from ambiguity. This may be done as follows:—

On the Measurement of the Velocity of Gases in Pipes.—Let A B, Fig. 1, be a portion of a pipe carrying a current of a gas in the direction of A B. Let C D be a small tube bent at right angles so that its open end C faces the stream of gas.

Fig. 1.



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* Some notes on the historical aspect of the subject of Fluid Velocity Measurement by means of the Pitot tube will be found in Appendix IV (page 287).

It is required to find a relation between the velocity and density of the gas stream on the one hand, and the pressure set up by this stream in C D on the other. The excess pressure in C D is supposed to be so small in comparison with the pressure in the stream itself that the gas may be treated like an incompressible fluid. Unless one knows just how the velocity of the stream is affected by the tube C D it does not appear possible to find a solution of the problem, but some approximation to a solution may be reached by making various assumptions.

For instance, assume that the motion of the gas is steady (non-turbulent) and that the stream lines impinge normally on the open end of the tube at C, and there terminate, the gas being annihilated after being brought to rest. In this case (no rotational motion) the question is one of forces and accelerations only.

Let the density of the gas be ρ and its velocity V (both in C.G.S. units), and let P be the resulting pressure just inside the boundary at C in dynes per square centimètre. Then in each second, momentum to the extent of

$$\rho V^2 \times \text{area}$$

is destroyed and this requires a pressure (that is, force per unit area) of P × area; equating these:—

$$\rho V^2 = P$$

or

$$V = \sqrt{\frac{P}{\rho}} \qquad (1).$$

In practice, however, the gas cannot be annihilated when it comes to rest; it has to be pushed out sideways, and the force to do this must come from the gas itself.

Consequently the power required must depend to some extent on the viscosity of the gas in question. Another way of stating the same result would be to say that, as the viscosity increases, the greater must be the momentum destroyed in producing sideway motion. A sort of cone of nearly motionless gas would form in front of the opening at C, and the sides of this cone might be regarded as being occupied in causing the stream lines to diverge so that the fluid could pass the obstacle, as is in fact apparent from

Professor Hele-Shaw's photographs.* The above relation would therefore appear to be an ideal one referring to a non-viscous gas, and the pressure P calculated from it would be merely an upper limit. The formula generally employed in connection with the Pitot tube differs from that given in equation (1) in making

$$V = \sqrt{\frac{2P}{\rho}} \qquad (2).$$

The argument in favour of this view is that if one holds a tube bent at right angles in a stream of water, so that one branch is horizontal and facing the stream and the other vertical, the water will rise to such a height as would give a velocity of efflux equal to the stream velocity; this is given by Torricelli's theorem, namely,

$$V = \sqrt{2gh} \qquad (3).$$

where g is the acceleration due to gravity and h is the height of the free surface above the point of efflux. If it be assumed that no energy is dissipated, but that the sum of the kinetic and potential energies is constant, the formula follows from D. Bernouilli's theory.†

If ρ the density of the fluid is introduced, equation (3) may be written

$$V = \sqrt{\frac{2gh\rho}{\rho}} = \sqrt{\frac{2P}{\rho}} \qquad (4).$$

Comparing (4) with (1) and applying both indifferently to all fluids, one notes that the pressure to be expected corresponding to a given velocity and density is

$P = V^2\rho$ by the assumptions leading to (1);

and $P = \frac{V^2\rho}{2}$ " " " " " (4).

But the pressure calculated by (1) is the pressure required to destroy the momentum of the impinging stream; and this of course does not occur in practice.

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[*] "Nature," vol. lx, page 443.

[†] Lamb's "Hydrodynamics," page 25.

The pressure required by (4) is clearly the pressure required to destroy half the momentum. If this is correct, a very ready way is obtained of estimating the effect of small obstacles of this kind on the energy of a stream of fluid.

Professors Poynting and Lamb have independently been good enough to draw the author's attention to the work of Kirchoff* and Lord Rayleigh,† from which it appears that the loss of momentum experienced by that part of a stream impinging on a lamina is 0·440 of the total momentum corresponding to the breadth of the lamina, the length being left out of consideration so as to get a two dimensional problem.‡

Equation (4) may be adopted as a working formula, by introducing a function of the velocity as a correcting term to represent in a rude way the result of the viscosity. Also in general the motion is turbulent instead of being steady, as assumed above, and the turbulence, other things being equal, is less the greater the viscosity. The equation will therefore stand, grouping these causes of imperfection under one symbol.

$$V = \phi(V)\sqrt{\frac{2P}{\rho}} \qquad (5).$$

Now it appears that in practice $\phi(V)$ is very nearly a constant whose value is nearly unity, when applied to velocities of air such as one usually deals with in pipes—say from 100 to 2,000 feet per minute in a pipe of one or two feet diameter—though the question has never been sharply examined. So far as the author has been able to find, it has never been suggested that the constant as generally used is a function of the velocity at all, but it seems reasonable to regard it as such.

For practical purposes, however, the author will begin by putting $\phi(V) = K$—where K is a dimensionless quantity approximating to unity, and the working formula becomes

$$V = K\sqrt{\frac{2P}{\rho}} \qquad (6),$$

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* "Zur Theorie freier Flussigkeitsstrahlen," Crelle T. 70, 1869.

† "Philosophical Magazine," May 1876.

‡ Lamb's "Hydrodynamics," page 109.

or if the manometric fluid is the same as the fluid whose velocity is the subject of measurement.

$$V = K\sqrt{2gh} \qquad (7).$$

It will be shown later that when dealing with such streams of gas as have been examined, the turbulence though marked is not such as to produce any great effect on the direction and magnitude of the instantaneous velocity of a particle forming part of the stream. In other words, the velocity of a particle of such turbulently moving streams is very nearly that of the stream itself. If the progress of a particle down the pipe were watched, it would not move in a straight line, but at every instant its velocity parallel to the axis would be far greater than its velocity in any other direction.

In the practical application of the Pitot tube to the measurement of the velocity of fluids flowing in pipes, one is met by the difficulty that the mean pressure of the fluid is generally above or below the atmospheric pressure. In order to ascertain the pressure set up in the Pitot tube, it is therefore necessary to make use of a differential manometer, one limb of which is connected to the Pitot tube and the other to a so-called "side-gauge." It has been shown by Heenan and Gilbert * that if the side-gauge be provided with a wide flange at the mouth, Fig. 7 (page 276), the condition is approximately satisfied. In many cases, practically where extreme velocities are not involved, it is just as good in practice to use a small hole bored through the side of the pipe carrying the stream under investigation, taking care to make the connection in such a manner that nothing projects beyond the inner surface of the pipe. This is practically equivalent to connecting one limb of the manometer to a layer of fluid at rest, and is the method which was generally employed by Darcy. It must be remembered that if the Pitot tube occupies the centre of the stream, the mean pressure at that point (and it is really this which is required) is different from the mean pressure at the edge of the stream, though both openings lie in the same cross-

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* Proceedings, Institution of Civil Engineers, vol. cxxiii, page 272.

section of the pipe. Except in extreme cases, however, this pressure difference is negligible. If a piece of thin walled tubing is inserted in the stream so as to lie with its long axis perpendicular to the stream lines, the moving fluid mixes at its mouth with the fluid at rest in the tube, and imparts some motion to it, tending to make it leave the tube. In consequence of this, a negative pressure or " suction " makes its appearance. If the walls of the tube are very thin and the tube perpendicular to the undisturbed stream lines, this suction amounts to nearly as much negative pressure as a Pitot tube placed at the same point would give of positive pressure. Most experimenters have tried to make use of this effect in order to increase the manometer reading, but experience shows that this is to court disaster. In the first place, there is no proper hydrodynamic theory of the mode in which the suction is set up to act as a guide in practice; and in the second, the slightest alteration of the shape of the mouth piece, or of its inclination to the stream lines leads to a variation in the amount of suction. The law connecting the velocity with the suction is also unknown, except in so far as the author has determined it.

The present investigation embraces the following points which will be dealt with briefly in the text, full details being given in each case in the appropriate Appendix.

1. The construction of a suitable manometer for observing the small differences of pressure to be dealt with.

2. The investigation of the influence of the shape of the Pitot gauge tip on the pressure set up.

3. The investigation of the reliability of side-gauges.

4. Relation between the velocity of air currents and the pressure developed in Pitot and other gauges.

5. Investigation of the distribution of velocity of gas streams in pipes.

6. Investigation of the distribution of velocity considered as a function of the velocity itself, and comparison of the results obtained when measuring streams for delivery by the Pitot tube, with the actual volume of gas delivered as measured by a gas-holder.

7. Some applications of the results obtained to actual engineering problems, including an account of a new system of inferential gas-meters.

In Appendix I (page 271) and Fig. 5 (page 273) an apparatus is described by means of which a difference of level of two liquids—supposing the same to be small—can be measured with certainty to within 0·01 millimetre. This result is obtained by using large enough areas to be free of capillary uncertainties, and by ascertaining the position of free liquid surfaces by adjusting them to contact with fine needle points. The apparatus is so built that the actual measurement is made by vernier callipers or micrometer screws, and all attempts at observing scales through the walls of glass tubes is avoided. An improved form of instrument on these lines is manufactured by the Cambridge Scientific Instrument Co., under licence from the author.

An apparatus, Appendix IV (page 287), consisting of a pipe about 109 feet long by 21 inches internal diameter of thin iron-tubing, was set-up. A fan driven by an engine was employed to produce air streams of various velocities in this pipe. The speed of the engine was kept constant by hand, and observations were repeated as often as was necessary to eliminate irregularities in the driving. Two extreme types of Pitot mouth-piece were investigated, one consisting of a parallel hole 1 mm. diameter bored through a bit of ebonite rod, and the other of a funnel-shaped nozzle with an opening of 2·3 cm. at the mouth tapering to about 0·5 cm. at the base 3·3 cm. away. Table 3 in Appendix II (page 278) shows that the differences in this extreme case are so small, that it may be taken that as between different cylindrical thin walled tube mouth-pieces they are negligible.

A large number of experiments intended to test the reliability of the flanged side-gauge were made by measuring the pressure difference from various points near the free end of the pipe against the atmosphere; both with a Pitot tube, a side-gauge with flange, and a side-gauge with flange having its aperture more or less closed by cotton wool. The result was that no suction could be detected with certainty in a case where a thin walled-tube would have given 3 or 4 mm. Owing to unsteadiness in engine driving it was impossible to do more than show that suction, if it existed, did so only to an extent of one or two per cent. of the amount produced by a similarly situated thin walled-tube. As the currents of air with which the author has to deal are such as will only give a few millimètres suction in any case, it was not considered worth while investigating the point for much larger velocities—more particularly in the light of Heenan and Gilbert's results.

On the other hand, during two years' constant experimenting on the distribution of gas and air velocity over the cross section of pipes, flanged side-gauges of various forms have been employed, as well as small holes bored through the walls of the pipes without internal projection, and the results obtained with these different forms of apparatus have been constantly compared. In no case has any material difference been noticed between the indications when using a flanged gauge and when using a small aperture. It is hardly likely that, if any appreciable suction exists, it would always occur to the same extent with all the gauges and apertures employed; and the conclusion is that for all practical purposes the suction is zero with a small aperture or with a flanged gauge made according to Heenan and Gilbert's description.

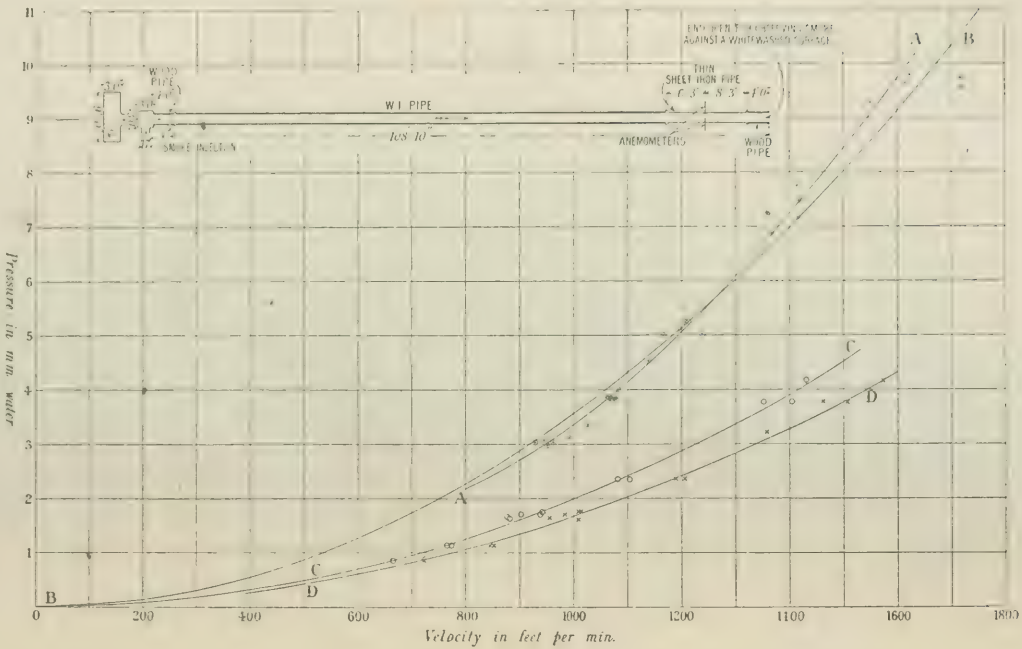
A combination of a Pitot tube with a side-gauge of thin-walled pipe giving the maximum suction has long been employed by those engaged in administering the Alkali Acts, Fig. 6 (page 275). For several reasons it was decided to begin by investigating this arrangement by means of currents of air of known velocity. The investigation required considerable experimental preparations; it is only necessary to state here that the method adopted consisted in blowing a current of air down a long pipe, and impressing the peculiarity of a smoke puff upon it at the entry end by the explosion of a minute charge of a special powder. The time signals were given electrically, and were recorded on a smoked glass plate chronograph of the usual kind. There was no difficulty, except in regard to keeping the engine at a sufficiently constant speed. The question arises as to how nearly the time taken by a puff of smoke in travelling down a pipe can be taken to represent the actual motion of air in the pipe.

The explosion was sufficient to distribute the smoke over the whole pipe section, but not large enough to project the smoke down the pipe with any velocity which could affect the results. The observer noting the arrival of the smoke noted the instant of its first appearance in the centre of the pipe ; and also the instant when it might be considered to have cleared off—a much more indeterminate epoch. The average of the periods covered between the first and last appearance of smoke is taken to represent roughly the mean time of transit—or to give a velocity which, when multiplied by the area of the pipe, will yield the "delivery." It will be shown later that the proper way to do this is from the velocity distribution curves. There is reason to believe, as will be shown, that the first appearance of the smoke is very approximately a measure of the velocity of the stream near the axis of the pipe, and it is therefore the maximum velocity with which one is here concerned and which operated on the gauges situated at the centre of the pipe. A glance at the curves AA, BB, Fig. 2 (page 251), giving the results with the Fletcher gauge, will make it clear that with this particular set of gauges at all events—the relation between gauge reading P, and velocity V—in any units is not $P = KV^2$, where K is a constant, but $P = KV^n$, where n is greater than 2.

Subject to the above limitation, it appears that the suction is, as assumed by other writers, nearly equal to the Pitot member pressure, or the gauge reading is about double of that due to the Pitot tube alone. It soon became obvious that the failure of the Pitot and suction combination to give results expressible by the simple formula quoted above, as well as the dependence of the results on the particular suction member chosen, rendered it hopeless to pursue this investigation. Accordingly a second series of experiments was instituted; this time using a Pitot tube and flanged side-gauge, curves CC, DD, Fig. 2 (page 251). The results are so consistent with the expression $P = KV^2$, that it was not possible to draw a curve according to this formula and cutting the experimental curve which did not coincide with the latter. In other words, within the limit of the experimental errors—the above expression exactly covers the behaviour of the Pitot tube. If one refers to equation 4

FIG. 2.—*Curves showing the relation between Velocity and Pressure.*

AA. Indicated by Fletcher Tubes. Maximum Velocity Curve fitting observations best.
BB. „ „ „ „ Deduced from Formula $KV^2 = P$.
CC „ „ Pitot Tube and Flanged Gauge. Mean Velocity Curve.
DD. „ „ „ „ „ „ „ Maximum Velocity Curve.



(page 247) and puts in the values for the density of air actually employed in the experiment, namely, barometer 760 mm., and air half saturated at 16° C., it is found that the curve drawn to fit the observations is expressed by

$$V = 771 \sqrt{\text{Pressure difference in mm. of water}}.$$

V being in feet per minute. The final result is velocity in feet per second

$V = 12 \cdot 45 \sqrt{\text{Pitot tube pressure in mm. of water}}$ for air under standard conditions. If the air be taken as half saturated at 760 mm. pressure and at 16° C., the constant becomes 12·53. This is the same as equation 4, if it is written—

$$V = 0 \cdot 9739 \sqrt{\frac{2P}{\rho}}$$

where V is the velocity in cm. per second; P is the Pitot tube pressure in dynes per cm.^{2}; and ρ is the density of the gas in grammes per cm.^{3}

The constant 0·9739 indicates possibly that the flange-gauge does give a slight suction in spite of all efforts to the contrary; it is hardly likely that the Pitot tube pressure should exceed the maximum laid down in equation 4.

(5). *The Mode of Motion of the Gas Stream.*—It is generally assumed in practice that currents of gas in pipes are in turbulent motion, at all events for velocities of engineering importance. It seemed to the author desirable to obtain some definite information on this point, before endeavouring to interpret the results of the measurements made by observing the smoke of small explosions.

For this purpose a gentle stream of smoky air was introduced in the main stream of the experimental pipe above described. The smoke employed was phosphorous pentoxide which gives a very persistent fume, and is easily produced by placing a little burning phosphorus on the bottom of a small tin canister, through which the air is driven on its way to the main stream. The smoky air was cooled down on its way to the experimental pipe and was led into the main stream by means of a sort of facing gauge, but in this case facing down stream. The inlet was about twelve feet from the delivery end of the experimental pipe. The progress of the mixing of the smoky air with the rest of the stream could be observed through some holes in the side of the pipe, and by looking in at the open end. The large diameter of the pipe (22 inches) was of service in this connection.

It was found that the smoke emerged from the pipe as a stream about 15 inches in diameter when the fan made 140 revolutions per minute. The air current was varied from this point to a velocity corresponding to the lowest velocity observed, but in all cases the smoke came through in a thick column. Since this only required a length of 12 feet, it is clear that, in interpreting the velocity experiments made on over 100 feet of pipe length, it is safe to regard the smoke produced by the explosion and the air as being thoroughly mixed up.

Interpretation of Velocity Experiments.—At the moment of explosion the smoke is distributed in a more or less symmetrical manner across the pipe section, so as to form a plug of smoky air filling a certain length of pipe. In the case of viscous flow, as this plug passes along it gets drawn out at the central part, becoming cigar shaped in front, so that by the time it reaches the open end of the pipe it forms a hollow shell. The turbulence of the stream examined however intervenes to equalise the motions of the various smoke particles, so that what is seen at the open end of the pipe is a thin leading stream in the centre quickly broadening to an apparently solid cloud, and ending in some whisps of smoke clinging to the sides of the pipe.

It has been assumed that the leading stream consists of those particles which have not deviated appreciably from a central path, and therefore fairly represent the average velocity of the central filaments. Similarly the final trace of smoke represents the motion of the air close to the walls of the pipe. It is estimated that about one-thousandth part of the smoke actually employed could not escape detection, and if the distribution of the velocities of the smoke particles be regarded as subject to the law of distribution of errors, it appears that there is every reason to suppose that the above assumptions are approximately correct.

The "mean velocity" as tabulated in the experiments described is obtained by adding together the time required for the first and last appearance of smoke and dividing by 2. This is quite arbitrary, because no doubt some smoke will continue to be given off by the sides of the pipe for an infinite time, but this again is seen to be unimportant in view of the rapid way in which the number of particles having velocities differing from the mean falls off as the degree of deviation increases. The mean velocity is thus roughly (in spite of the arbitrary way of ascertaining it) the velocity with which the main plug of smoke travels down the pipe, and is also roughly the velocity which must be multiplied by the area of cross section to get the pipe delivery. From a reference to the Tables and curves, Fig. 2 (page 254), it will be seen that the mean velocity thus estimated bears a fairly constant ratio to the maximum velocity.

On the Distribution of Velocity Across a Pipe Section.—It was shown by Darcy that in the case of water flowing through a long smooth pipe, there exists a circle whose radius is 0·689 of the radius of the pipe, which circle is the locus of points through which the stream has the mean velocity. The mean velocity is defined as that velocity which, when multiplied by the area of section of the pipe, will give the delivery. It has hitherto been usual to apply this result of Darcy's to the flow of gases generally, without investigating whether the condition stipulated as to length of pipe is sufficiently satisfied.

It may be stated at once that in dealing with ordinary currents of air or gas, as occurring in every-day practice, the condition as to length, or some other condition, is not satisfied, and it becomes necessary to investigate the distribution of velocity for each particular case as it arises. Assuming that this has been done in any particular case, the further question arises as to whether the distribution of velocity remains similar to itself as the velocity varies, for, unless this is the case, the whole system of gauging by the Pitot tube would be for metering purposes without any practical significance.

The author's experiments on this subject have now extended over more than two years, and the result is unmistakable, namely, that within the range of velocities that have been examined, extending from 600 to 3,500 feet per minute, the distribution of velocity is not a function of the velocity itself, not even in those cases in which it is very irregular and widely different from the ideal distribution as formulated by Darcy. Some of the experiments were made with currents of air supplied by a fan driven electrically, others by timing the fall of a gas-holder of about 22,000 cubic feet capacity, the latter, of course, having the advantage of supplying air or gas at a known rate, and thus giving a complete control of the whole gauging.

In regard to the investigations made by means of a fan, the great difficulty lies in securing uniformity of driving. A great deal can be done by the observer having electric measuring instruments under his eye, and regulating resistances under his hand: but the most satisfactory method of all is to employ a subsidiary Pitot tube and side-gauge in connection with a delicate manometer, Fig. 4 (page 272). Practically the same experimental conditions as those used by Darcy were employed throughout the investigation. A steel tube about ¼ inch diameter was provided at the centre of its length with a small mouth-piece at right angles to its axis, so that, when it was placed across an air stream, the mouth-piece faced the stream and could be moved to any point in a diameter of the pipe under investigation. Suitable scales were placed in position outside the pipe, so that the position of the mouth-piece could be accurately ascertained at any time. The side-gauge was sometimes used in the form of a flanged gauge, and sometimes as a simple opening into the pipe as already described.

In regard to the reduction of the observations, the usual course was to gauge right across one or two diameters of the pipe, taking observations most frequently as the Pitot tube approached the walls of the pipe. From these observations the velocity distribution-curve was plotted, Figs. 8 and 9 (page 286). The delivery of the pipe was ascertained by breaking up the section into a sufficient number of shells, finding the mean velocity for each shell from the curve and then computing its delivery. As the distributions were often irregular, this was practically the only way, and it was found that in general it was amply sufficient to sum about 15 shells in order to obtain a result within less than 1 per cent. of the true value. The number of shells necessary of course depended on the form of the distribution curve.

In Appendix III (pages 279 to 286) will be found a complete set of the results of gauging a particular stream, together with examples of the distribution curves. The whole investigation is summarised in Table 1 (pages 260–265).

An inspection of the Table will, it is believed, justify the following propositions:—

1. The radius of the circle of mean velocity is about 0·775 of the radius of the pipe through which gas is flowing, in the case of pipes which are not infinitely long but comparable in length with those employed in connection with gas-producer plants.

2. One case of a gas main 15·75 inches in diameter was examined at a distance of about 10 yards from the nearest bend; in this pipe the radius of mean velocity was certainly about 0·9 of the radius of the pipe.

3. In no case was a radius of mean velocity so low as 0·689 actually found.

4. Whatever the distribution of velocity observed at any one velocity may be, this persists unaltered through a wide range of velocity covering the cases which occur in ordinary practice. The highest velocity examined was 3,600 feet per minute, and the lowest for which accurate results were obtained about 600 feet per minute.

5. The ratio of mean to maximum velocity is unexpectedly constant over a wide range of velocity and very varied mode of distribution. The average value is about 0·873.

6. Since in any practical case, where accuracy is necessary, a calibration of the pipe for distribution of velocity must be made, it is immaterial where the Pitot tube is placed. Since, however, the velocity is in general greatest at the centre, it is convenient to

(*Continued on page 266.*)

TABLE 1 (*continued to page* 265).

Date.	Diameter of Pipe. Inches.	Number of shells calculated.	Maximum velocity in feet per minute.	Mean velocity from gaugings. Feet per minute.	Radius of mean velocity. Radius of pipe = 1·0.	$\frac{\text{Mean velocity.}}{\text{Maximum velocity.}}$	Delivery by gauging. cub. ft. per min.
Dec. 1901.	8·706	8	1218	1130	0·8432	0·9278	503·9
14 Jan. 1902.	35·70	8	1135·2	1034·6	0·8429	0·9114	7188·16
Aug. 1902.	21·0	7	2005·8	1875·4	—	0·935	4511·4
11–14 Mar. 1902.	21·3	13	119·6	112·5	0·8520	0·941	—
11–14 Mar. 1902.	21·3	13	650·2	617·9	0·8474	0·95	—

TABLE I.

Delivery otherwise ascertained.	Error as per cent. of true delivery.	Remarks.
491·4	2·5 (too large)	*Air.*—The pipe was of sheet-iron, 6 feet long, and forming the junction between two other pipes each 12 inches diameter, the connection being by flanged coupling. The gauges were at the centre of the 6-foot length. The gasholder only took 14 minutes to fall, necessitating about eight fillings. Barometer 756·4 mm. Temperature 8·5° C. Observations on one diameter.
7302	1·6 (too small)	*Mond Gas.*—A series of observations continued over a fortnight were made on a large gas-main taking the whole produce of the producers. During this time systematic weighings and samplings of the fuel, gas, ashes, dust and tar were made. All these samples were analysed. The actual delivery of gas is based on the carbon known to have been gasified, and the analysis of the gas giving the carbon per cubic foot. Observations on one diameter.
4510	0·37 (too large)	*Air.*—The mean of two sets of measurements made during the testing of a large alternator (Journal, Elect. Eng. 1903). The measurement was made in a sheet-iron pipe about 15 feet long, the air being blown in by a fan. The calculated delivery is based on observation of the rise of temperature of the air stream; the heat-supply being electrical and accurately measured by a Kelvin balance. Observations on one diameter.
—	—	*Air.*—The pipe was supplied with a muslin diaphragm, so as to test a regular but forced mode of distribution. The muslin was at a distance of 16 ft. 3 ins. from the gauges, and the air-current was produced by a fan. Observations on one diameter.
—	—	*Air.*—Same as last, but a higher velocity.

TABLE 1 (*continued on next page*).

Date.	Diameter of Pipe. Inches.	Number of shells calculated.	Maximum velocity in feet per minute.	Mean velocity from gaugings. Feet per minute.	Radius of mean velocity. Radius of pipe = 1·0.	$\frac{\text{Mean velocity.}}{\text{Maximum velocity.}}$	Delivery by gauging. cub. ft. per min.
—	15·75	5	1912	1850	0·893	0·967	—
10 Nov. 1902.	6	16	1667	1437	0·766	0·862	—
14 Nov. 1902.	6	16	666·7	589·7	0·768	0·8845	—
18 Nov. 1902.	6	16	2675	2341	0·773	0·875	—
20 Nov. 1902.	6	16	3642	3187	0·765	0·875	—
3 Dec. 1902.	12	16	2771·5	2455·5	0·773	0·8861	—
8 Dec. 1902.	12	16	1714·2	1526	0·773	0·8872	—
12 Dec. 1902.	12	16	2594	2332	0·801	0·899	—

(continued on next page) TABLE I

Delivery otherwise ascertained	Error as per cent. of true delivery.	Remarks
—	—	*Mond Gas.*—Test made to see whether the different viscosity of Mond Gas would have any appreciable effect on the resulting distribution of velocity. The observations were repeated three times along one diameter of the pipe.
—	—	*Air.*—Distribution in a smooth cast-iron pipe fed by a fan blowing first into a box to which the pipe was connected. Gauges 16 feet from the box. Observations taken at 50 points on the horizontal diameter.
—	—	*Air.*—As above. Lower velocity.
—	—	*Air.*—Ditto. Higher velocity.
—	—	*Air.*—Ditto.
—	—	*Air.*—A smooth cast-iron pipe—arranged as in the last series of experiments. Gauges 17·5 feet from box. Forty-four observations across a diameter.
—	—	*Air.*—Ditto. Same series of experiments as last.
—	—	*Air.*—Ditto.

TABLE 1.

Date.	Diameter of Pipe. Inches.	Number of shells calculated.	Maximum velocity in feet per minute.	Mean velocity from gaugings. Feet per minute.	$\frac{\text{Radius of mean velocity.}}{\text{Radius of pipe} = 1\cdot0.}$	$\frac{\text{Mean velocity.}}{\text{Maximum velocity.}}$	Delivery by gauging. cub. ft. per min.
8 Jan. 1903.	6	16	1319·4	1064·6	0·737	0·807	1899
1 Jan. 1903.	6	16	2472·6	1953	0·721	0·790	1835·5
1 Jan. 1903.	6	16	2406·3	1961	0·725	0·815	1866
20 Feb. 1903.	6	16	998	976	0·845	0·978	—
24 Feb. 1903.	6	16	1692	1545	0·796	0·913	—
15 May 1903.	6	16	325·1	298·1	0·863	0·917	—
11 May 1903.	6	16	2429	2205	0·796	0·908	—
21 May 1903.	6	16	2664	2411	0·793	0·905	—

(*concluded from page* 260) TABLE 1.

Delivery otherwise ascertained	Error as per cent. of true delivery.	Remarks
1881·3	0·34 (too high)	*Air.*—Six-inch cast-iron pipe supplied by gasholder. Fourteen observations across a horizontal diameter.
1880	2·9 (too low)	*Air.*—Ditto.
1880	1·28 (too low)	*Air.*—Ditto.
—	—	*Air.*—Six-inch pipe with baffle. Distance box to gauges 35 feet, and from baffle to gauges 3 feet 6 inches.
—	—	*Air.*—Ditto. Box to baffle 29 feet—baffle to gauges 6 feet.
—	—	*Air.*—Ditto. The velocity is too small for accuracy. The figures obtained must be regarded as approximate only.
—	—	*Air.*—Ditto.
—	—	*Air.*—Ditto.

place the tube mouth-piece at this point. If it be considered sufficient to dispense with a calibration, then the results indicate that it is better to place the Pitot mouth-piece on the circle of radius 0·775 (radius of pipe) than to place it at the centre and to assume a ratio of mean to maximum velocity of 0·873.

The whole investigation was directed to elucidate the problem of how best to measure the delivery of producer-gas by large mains. It was therefore considered that a series of comparisons of delivery, as deduced from Pitot tube readings, with the same quantity as measured by a gas-holder, would be desirable. A six-inch iron pipe was taken and calibrated, and six experiments were made by allowing a gas-holder to empty itself through the pipe. Table 2 (page 267) is intended to show the sort of accuracy attainable in ordinary every-day practice, as well as the degree of consistency that may be looked for in a series of measurements of this kind.

Some applications of the Measurement of Air and Gases in Practical Engineering Work.—The first application is of course to the measurement of producer gas, and indeed the whole investigation was directed to that end. One illustration has been given in the summary in the text (page 260) of the measurement of the delivery of a certain gas-main, and it is not necessary to say anything more on this head. As soon, however, as it was firmly established that a Pitot tube in an invariable position could give an accurate measurement of the delivery, a hope arose that an apparatus might be constructed which would give a time integration of the square root of the Pitot-tube pressure and hence of the delivery over any period of time. This amounts to making a gas-meter working by Pitot-tube pressure. The problem has been solved in many ways, some of the resulting mechanisms being described in British Patent No. 21312 of 1902. The instrument which has had the longest trial (eighteen months) in actual work is selected here for description, because it has shown itself reliable over the whole of the period, and may be considered to have reached a stable form.

The principle employed is the following: The Pitot tube and side-gauges being placed in a calibrated gas-main, a small pressure

TABLE 2.

Observations of Measured Delivery from Gas-holder through 6-inch pipe by Pitot Tube Measurement of the Maximum Velocity of Flow at the Centre of the pipe. The Average ascertained value of the Ratio of Mean to Maximum Velocity, viz., 0·8038 *is used throughout. The Maximum Velocity is obtained from the Formula:*

$$\textit{Velocity in Centimètres per Second} = 1\cdot377\sqrt{\frac{98\cdot1 \times \textit{pressure in mm water}}{\textit{density of air}}}$$

No.	Distance of fall of Holder	Time of fall of Holder	Total air delivered by Holder	Average of all Observations at centre of 6-inch pipe for Pressure in mm of Water made during one fall of Holder.	$\sqrt{\text{Pressure Difference in mm of Water}}$	Density of air: grams per cubic centimètre	Maximum velocity by Pitot tube	Total gas Delivered by Holder —by gauge observations	Error of gauge estimate —per cent. of true Delivery.
	Feet	Minutes.	Cubic feet				Feet per minute.		
1	6·0	9·023	1881·3	2·86	1·691	0·001250	1284·0	1829	2·78 (Low)
2	6·687	5·25	2096·0	11·91	3·451	0·001275	2594·4	2149	2·55 (High)
3	6·0	4·166	1881·0	14·22	3·771	0·001275	2835·0	1864	0·9 (Low)
4	6·0	4·79	1881·0	10·68	3·268	0·001284	2448·4	1850	1·65 (Low)
5	6·0	4·905	1881·0	9·83	3·137	0·001261	2370·6	1834	2·5 (Low)
6	6·0	4·969	1881·0	9·872	3·142	0·001261	2374·8	1859	1·17 (Low)

Note.—In series 6, a wider Pitot tube was employed. Average error 1·38 Low. This may be regarded as a systematic error.

difference is set up. This pressure difference is brought to bear on a bell, which is hung and tied down by springs and partially immersed in oil like an ordinary gas-holder. The tubes are so connected that the pressure difference tends to depress the bell. The force acting on the bell is continuously balanced electrodynamically by an arrangement of six coils of wire, four fixed, and two movable, carrying a current and so attracting and repelling each other. By the construction of the meter, the current is self-adjusting so that the pressure difference is always exactly balanced by the electrodynamic force.

Let C be the current, P the pressure difference in any units, A the area of the section of the bell, K a constant. Then when the balance is exact

$$PA = KC^2;$$

or

$$P = C^2 \times \text{constant} \qquad (2).$$

It has already been seen, however, that with a properly calibrated gas-pipe the rate of delivery of gas ($\dot{D}$) at any instant is

$$\dot{D} = \sqrt{P} \times \text{constant},$$

or

$$P = \frac{\dot{D}^2}{k} \qquad (4).$$

Comparing (2) and (4)—

$$\dot{D} = C \times \text{constant} \qquad (5).$$

The delivery over a period of time T in any units is—

$$\int_0^T \dot{D}\, dt = \chi \int_0^T C.\, dt.,$$ where χ is a constant.

Now if the current flows through an ampère-hour meter, this instrument gives us the value of $\int_0^T C.\, dt.$, and hence, when χ is known, the number of cubic feet or cubic mètres of gas delivered can be found from the reading of the ampère-hour meter.

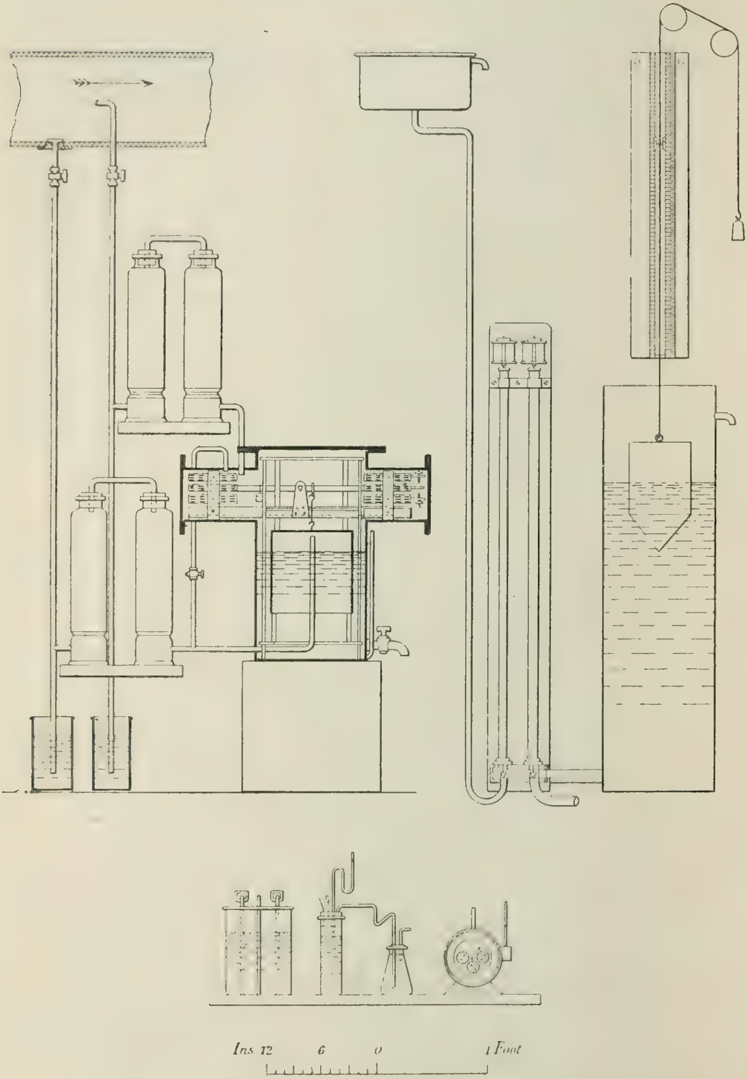
To calibrate the meter, it is only necessary to know the area of the cross section of the bell and the current required to balance any particular pressure difference. Of course the distribution curve of the pipe where the Pitot tube is placed must also be known, and the mean density of the gas where it passes the Pitot tube. All these quantities are obtained once and for all.

The drawing, Fig. 3 (page 270), is to scale and is practically self-explanatory, the electrical connections being well understood are omitted for the sake of distinctness. The gas, both from the Pitot tube and side gauge, passes through appropriate filters to separate tar and water without interposing a back pressure, and is led to the inside and outside of the bell placed in its casing. The bell is attached to the arm of the electrodynamic balance and the counterpoise is adjusted till some of the weight of the bell is taken by the balance arm. The end of the arm is provided with contact studs playing between two other fixed contacts, so that a very small want of balance of the arm brings one or other set of contacts into play. The contacts work separate circuits so that water is led into or out of a vertical cylinder. Floating on the water in the cylinder is a float which, by means of a cord, varies a resistance in the balance circuit.

The balance circuit contains some form of ampère-hour meter—most economically of the electrolytic type—from which readings can be taken. In practice it is found that a copper voltameter is as good as anything, the plates being changed and weighed by one of the boys who do the testing at the producer plant; it takes about ten minutes. The trouble of this operation is really not felt, and greater accuracy is thus secured than could be got otherwise, except by using a more elaborate ampère-hour meter for which larger currents would be required than are actually needed in the balance. The apparatus does not seem to get out of order, and is in fact very reliable in practice, the only drawback being that it needs a supply of a few buckets of *clean* water every day and a source of electric current not liable to interruption. If the latter be at 100 volts, about 1/10th ampère is found to be a convenient current to employ. Experience obtained with various forms of mechanically integrating meters has not as yet extended over a sufficient period to justify the author in bringing them before the Institution.

Fig. 3.

Pressure-Measuring Apparatus.



There is, however, a subsidiary piece of apparatus which in many instances is more useful than an integrating meter. This is called a "stream-gauge" by the author and is analogous to the anemometer of Mr. W. H. Dines in operation, though the construction is very different. The stream-gauge, Fig. 4 (page 272), is provided with a scale so divided that the angular distance from the zero is proportional to the square root of the numbers from 0 to 100. In general a circular dial divided in this manner is employed, and by a simple construction the motion of a spring bell of suitable dimensions is brought to bear on the needle. Both this instrument and the integrating meters are manufactured under license by Messrs. Chamberlain and Hookham of Birmingham.

The author desires to express his thanks to his assistant, Mr. Bradbury, for making most of the measurements referred to in the Paper.

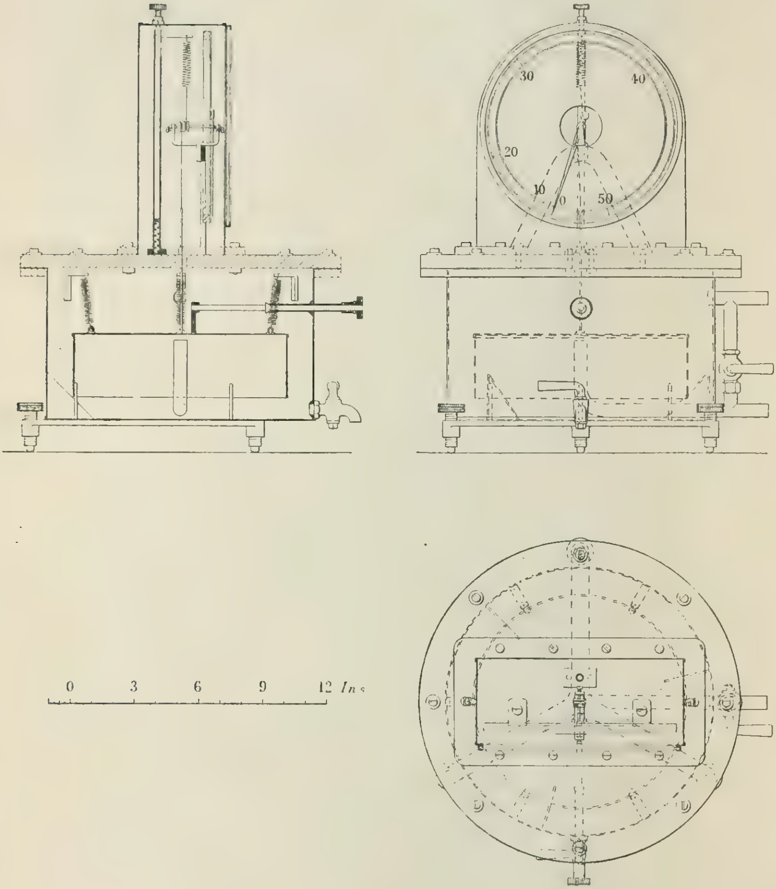
The Paper is accompanied by five Appendices, and is illustrated by 9 Figs. in the letterpress.

APPENDIX I.

Apparatus.—As in the case of everyone else who has approached the subject, an initial attempt was made to get a pressure-gauge suitable for measuring the few millimètres difference of water level generally available.

The principle adopted was the following. The wide-mouthed bottles, Fig. 5 (page 273), were half filled with coloured water and connected by a syphon. The facing and side-gauge tubes were put in communication respectively with a free space in the two bottles. The level of the liquid was ascertained in each bottle by adjusting a movable needle-point so as just to touch the surface. The needle-points formed the terminations of two cylindrical rods working in V grooves, and prevented from turning about their long axes by means of arms carrying studs which were kept in contact with a flat surface, whose plane was parallel to the axes of the V grooves. These arms formed two jaws, whose distance apart could be measured by a vernier callipers. The rods carrying the needle-

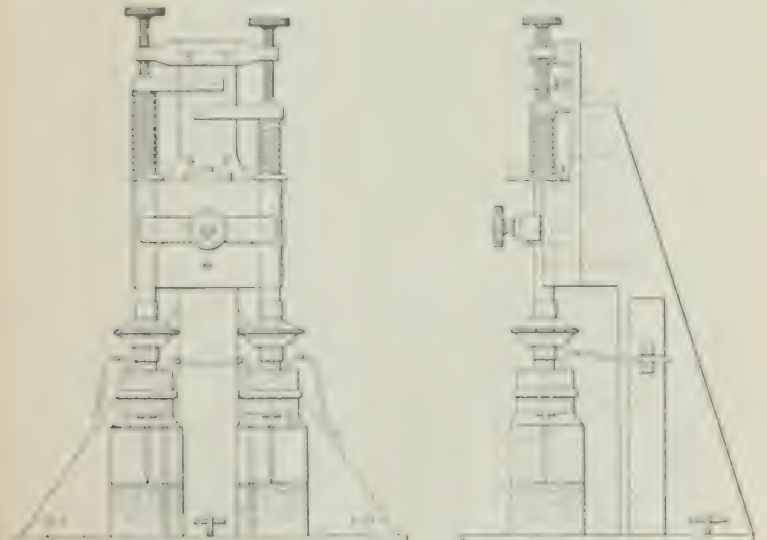
Fig. 4.—*Stream-Gauge (Threlfall).*



points could be depressed by means of milled-headed screws working on their upper ends, the return motion being effected by spiral springs. The needle-points were paraffined so as to prevent their carrying a drop of water after every adjustment, and this precaution succeeded fairly well. The needle-points were afterwards bent through 180° so as to meet the surface from the under side,

FIG. 5.

Apparatus for Measuring Difference of Level of two Liquids to within 0·01 mm.



but the results were not more consistent, and as the apparatus was decidedly less accurate in a bad light, the method was given up. It might be better to use small balls instead of points, if the contact is made below the surface.

A large number of settings of this gauge were observed, both water surfaces being open to the air. The following is the first set of observations of the distance between the external surfaces of the jaws, the gauge being reset for each observation.

19·40 mm.
0·38 mm.
0·38 mm.
0·38 mm.
0·40 mm.
0·39 mm.
0·40 mm.
0·40 mm.
0·41 mm.
0·40 mm.
0·38 mm.

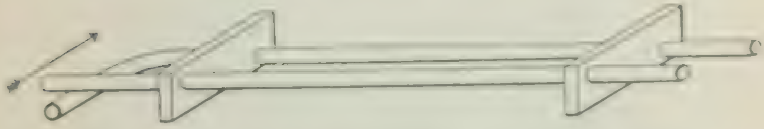
This set was taken before any practice had been obtained; with a little practice one can be quite certain of being within ±0·01 mm. By using immersed spheres, attending to the illumination, &c., no doubt the accuracy could be considerably increased, but the accuracy obtained being ample for the purpose no such refinements were attempted.

The advantage of the instrument is that the difference of level is ascertained by the most direct mechanical measurement, and is free from errors due to imperfect graduation of glass scales—irregular refraction through the walls of glass tubes, capillary uncertainties, &c. Some years ago the author examined one of the Darling Brown and Sharp vernier callipers, and found its errors quite negligible for the present purpose. Consequently no examination of the callipers was made on this occasion. In making a fresh instrument it would be more convenient to set the needle-points by micrometer screws. This course has been adopted in the instruments now made by the Cambridge Scientific Instrument Co., which can be set to within ±0·003 mm.

APPENDIX II.

Influence of Shape of Gauge Tubes.—In the beginning the author's ambition was limited to connecting the velocity of a stream of air in the experimental pipe with the indications of the anemometer. It was not expected to find anything more than a purely empirical relation, and for this purpose the choice of a gauge was limited only by the condition that the pressure differences obtainable should be as large as possible, and that the gauge should be of such a pattern that it could be easily and exactly reproduced if it met with an accident. The Fletcher form of gauge appeared likely to give the largest pressure-differences, and experiments were made with glass tubes in order to find whether slight differences in construction would affect the resulting indications, and, if so, to what degree. The result of these trials, which need not be further considered in view of Heenan and Gilbert's results, was to show that the best results appeared to be given by pressure and side-gauges, both made of thin tubes and terminated by edges lying in a plane perpendicular to the axis of figure, that is, cut clean across. Considerable differences were found in the pressure differences registered, and it was obvious that glass was, from its fragility, by no means an ideal material. Consequently, two standard sets of Fletcher gauges were made out of brass tube as nearly alike as possible, and were so rigidly built that nothing but a serious accident could harm them, Fig. 6. These gauges will be referred to as Fletcher "A" and Fletcher "B." The Swan apparatus was too light and fragile for the purpose of the experiment, or it would have been employed. It was of course at once noticed

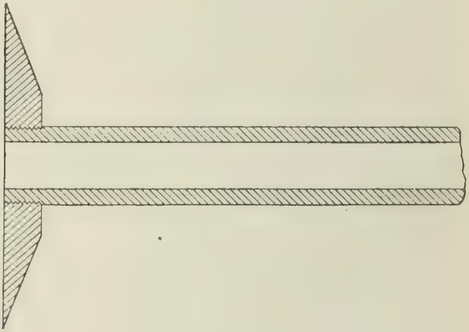
Fig. 6.—*Fletcher Gauges.*



that the differences in the gauges were much more dependent on the suction than on the pressure member. After considerable experience had been obtained the matter was re-examined carefully, the examination being directed now to the pressure tube alone, on the ground that for it some sort of a theory existed while there was none in the case of the suction tube. The difficulty of the comparison lay in the fact that the simple form of engine employed to drive the fan worked irregularly, and it was necessary to regulate it by hand according to the indications of the tachometer; even then speed variations of small period made it necessary to multiply the observations.

A side-gauge with a sharp flanged edge, Fig. 7, was used throughout these trials, and was situated close to the side of the experimental tube, and simply served to give a standard of pressure. The question as to the behaviour of the flanged gauge itself may be reserved for a moment, as it was common to all the experiments.

FIG. 7.—*Side-tube Gauge.*



Three gauges were compared with the facing-gauge of Fletcher A:—

1. A. The facing-gauge of Fletcher B.
2. D. Ditto. The mouth provided with a cone opening outwards. This cone was 3·3 cm. long and had an opening of 2·30 cm.

E. Ditto. The end plugged with ebonite through which a cylindrical hole 1 mm. diameter was carefully bored.

The following is a specimen table of comparisons:—

Comparison of facing-gauges.

Engine speed 100 revolutions per minute.

Air temperature 16° C. throughout, and barometer sufficiently constant to be regarded as exactly so.

Observations taken alternately on A combined with flange-gauge, and on D combined with flange-gauge.

	A gauge. Reading of Micrometer Gauge.		D gauge. Reading of Micrometer Gauge.
	21·36		21·41
	21·30		21·41
	21·34		21·40
	21·34		21·40
	21·31		21·40
	21·33		21·40
Mean . .	21·33	Mean . .	21·403
Zero Reading	19·37	Zero Reading	19·38
Difference .	1·96	Difference .	2·02

Pressure difference, 1·96 mm. Pressure difference, 2·02 mm.

Table 3 (page 278) gives a summary of results similar to the foregoing, but there is no object in reproducing the individual observations, since an idea of the consistency of the results can be obtained from the above, which is neither better nor worse than the others.

The conclusion to be drawn is that a conical gauge reads a little higher, and a gauge with very thick walls and a small hole lower, than the standard cylindrical thin-walled pattern. If one considers the vast difference in the form of the openings, one may agree with other writers that the form of the pressure tube has not "much" influence, how much can be judged from the Table. The probability

TABLE 3.

Facing-gauges compared each in conjunction with the same flange-gauge.	Engine speed. Revs. per minute.	Corresponding speed of air current in feet per minute approximate.	Mean pressure difference observed in mm. of water.	Number of observations.	Difference between pressures observed: positive when A gauge gave the larger reading.
					mm.
A	136	1218	2·191	6	– 0·1
D	,,	1242	2·591	6	
A	100	1080	1·96	6	– 0·06
D	,,	1096	2·02	6	
A	182	1208	2·44	4	+ 0·155
E	,,	1168	2·285	4	
A	138	1210	2·46	3	+ 0·30
E	,,	1132	2·16	3	
A	138?	1186	2·34	3	+ 0·28
E	,,	1112	2·08	3	
A	94	1002	1·69	3	+ 0·13
E	,,	966	1·55	3	

is, however, that for an exact physical investigation the proper course would be to use gauges of such shape as to give the maximum pressure difference and avoidance of Darcy's "Lost Motion." This idea, however, did not occur to the writer till the investigation was too far advanced to permit of a recommencement, particularly as ordinary thin-walled tubes were found to work with all needful accuracy.

APPENDIX III.

The accompanying Tables (pages 280 to 285) and curves, Figs. 8 and 9 (page 286), illustrate a typical investigation of the distribution of velocity in a 6-inch cast-iron pipe fed from a gas-holder. The velocity ranged from 1,320 to 2,470 feet per minute.

APPENDIX III.

TABLE 4.

Distribution of Velocity in 6-inch pipe attached to Gas-holder.

Anemometer 15 *feet from junction to large pipe.*

Maximum Velocity 1319·4 *feet per minute.*

Fig. 9 (page 286).

Distance from nearest side of pipe in inches.	Left of centre.	Right of centre.
	$\sqrt{\text{Manometer pressure difference in millimètres of water.}}$	
3	1·738	1·738
2	1·658	1·658
1	1·470	1·466
0·75	1·414	1·382
0·5	1·281	1·304
0·3	1·183	1·221
0·1	1·058	1·072
	Time required for gas-holder to fall 6 feet, 9′ 12·8″.	Time required for gas-holder to fall 6 feet, 8′ 58·3″.

APPENDIX III. (continued).

TABLE 2.

Delivery of 6-inch pipe attached to Gas-holder according to observations (Table 4, page 280).

Values of √ pressure taken from curve.

Fig. 9 (page 286).

No. of Shell.	Area of shell in square inches.	Mean of √ Maximum pressure differences in mm. of water.	Area of shell × √ pressure difference.
1	0·120	1·731	0·2175
2	0·377	1·727	0·6[illegible]
3	0·628	1·711	1·0[illegible]
4	0·880	1·6[illegible]	1·402
5	1·131	1·674	1·8[illegible]
6	1·382	1·640	2·279
7	1·634	1·617	2·641
8	1·886	1·582	2·981
9	2·13[illegible]	1·5[illegible]	3·30[illegible]
10	2·388	1·5[illegible]	3·6[illegible]
11	2·6[illegible]	1·490	3·797
12	2·890	1·374	3·971
13	3·14[illegible]	1·290	4·053
14	3·3[illegible]	1·196	4·057
15	1·791	1·106	1·9[illegible]
16	1·8[illegible]	1·0[illegible]	1·946
	28·274		39·0[illegible]

Barometer 744 mm.
Temperature 2·30° C.
Humidity 100 per cent.
Density of air 0·001261 grammes per c.c.

Total area × √ maximum pressure difference = 49·1[illegible].

Mean velocity / Maximum velocity = 0·80[illegible]. Position of point of mean velocity 0·7[illegible] radius from centre.

Area of section of gas-holder 312·7 square feet.

Total delivery of air for 6 feet fall of holder—by holder 1881·2 cubic feet.

„ „ „ „ „ —by gauges 1899 cubic feet.

Error of measurement as percentage of actual volume delivered 0·9[illegible] per cent., and the gauges give the higher result.

APPENDIX III. (*continued*).

TABLE 6.

Distribution of Velocity in 6-inch pipe attached to Gas-holder.

Anemometer 15 *feet from junction with large pipe.*

Maximum Velocity 2472·6 *feet per minute.*

Curve B_2, Fig. 8 (page 286).

Distance from nearest side of pipe in inches.	Left of centre.	Right of centre.
	√ Manometer pressure difference in millimètres of water.	
3	3·260	3·260
2	3·081	3·180
1	2·663	2·722
0·75	2·454	2·583
0·5	2·234	2·352
0·3	2·173	2·283
0·1	1·847	1·916
	Time required for gas-holder to fall 6 feet, 4′ 46″.	Time required for gas-holder to fall 6 feet, 4′ 48·4″.

APPENDIX III (*continued*).

TABLE 7.

Delivery of 6-inch pipe attached to Gas-holder according to observations (Table 6, page 282).

Values of $\sqrt{\text{pressure}}$ taken from curve.

Curve B_2, Fig. 8 (page 286).

No. of Shell	Area of shell in square inches.	Mean of $\sqrt{\text{Manometer}}$ pressure difference in mm. of water.	Area of shell × $\sqrt{\text{pressure}}$ difference.	
1	0·126	3·254	0·410	Barometer 742·0 mm. Temperature 14° C. Humidity 100 per cent. Density of air 0·0012[illegible] grammes per c.c.
2	0·377	3·249	1·225	
3	0·628	3·227	2·027	
4	0·880	3·194	2·811	
5	1·131	3·154	3·567	
6	1·382	3·100	4·284	
7	1·634	3·078	5·029	
8	1·885	3·017	5·687	
9	2·136	2·856	6·101	
10	2·388	2·746	6·557	
11	2·639	2·620	6·914	
12	2·890	2·462	7·116	
13	3·142	2·306	7·244	
14	3·393	2·112	7·166	
15	1·791	1·940	3·474	
16	1·855	1·810	3·358	
	28·274		72·829	

Total area × $\sqrt{\text{maximum pressure difference}}$ = 92·48 [illegible]

$\frac{\text{Mean velocity}}{\text{Maximum velocity}} = 0·79$. Position of point of mean velocity 0·721 radius from centre.

Area of section of gas-holder 312·7 square feet.

Total delivery of air for 6 feet fall of holder—by holder 1876·2 cubic feet.

" " " " " —by gauges 18[illegible] cubic feet.

Error of measurement as percentage of actual volume delivered is 2·9 per cent. and the gauges give the lower value.

APPENDIX III. (*continued*).

TABLE 8.

Distribution of Velocity in 6-inch pipe attached to Gas-holder.

Anemometer 15 feet from junction with large pipe.

Maximum Velocity 2406·3 feet per minute.

Curve B_1, Fig. 8 (page 286).

Distance from nearest side of pipe in inches.	Left of centre.	Right of centre.
	√ Manometer pressure difference in millimètres of water.	
3	3·169	3·177
2	3·050	3·046
1	2·566	2·670
0·75	2·526	2·538
0·5	2·298	2·356
0·3	2·241	2·149
0·1	1·879	1·825
	Time required for gas-holder to fall 6 feet, 4′ 53·2″.	Time required for gas-holder to fall 6 feet, 4′ 48·5″.

APPENDIX III (concluded).

TABLE 9.

Delivery of 6-inch pipe attached to Gas-holder according to observations, Table 8 (page 284).

Values of √ pressure taken from curve.

Curve B_1, Fig. 8 (page 286).

No. of Shell.	Area of shell in square inches.	Mean of √ Manometer pressure difference in ins. of water.	Area of shell × √ pressure difference.
1	0·028	2·113	0·058
2	0·277	2·747	0·810
3	0·528	2·406	1·270
4	0·880	2·492	2·233
5	1·161	2·074	2·408
6	1·452	2·868	4·161
7	1·623	2·977	4·802
8	1·884	2·514	4·737
9	2·166	2·862	6·200
10	2·288	2·732	6·249
11	2·650	2·601	6·892
12	2·860	2·506	7·200
13	3·142	2·280	7·000
14	3·085	2·144	7·292
15	1·710	2·040	3·474
16	1·850	1·757	3·250
	28·274		72·082

Barometer 752 mm.
Temperature 14° C.
Humidity 100 per cent.
Density of air 0·00121 grammes per c.c.

Total area × √ maximum pressure difference = 80·11.

$\frac{\text{Mean velocity}}{\text{Maximum velocity}} = 0·8148$. Position of point of mean velocity 0·725 inches from centre.

Area of section of gas-holder 312·7 square feet.

Total delivery of air for 6 feet fall of holder—by holder 1876 cubic feet.
" " " " " " —by gauges 1856 cubic feet.

Error of measurement as percentage of actual volume delivered is 1·06 per cent. and the gauges give too low a value.

FIG. 8.

Distribution of Velocity Curves for 6-inch pipe attached to Gasometer. 1 *Jan.* 1903.

No. 1. Mean Position 0·725 r. from centre. Ratio of Mean to Maximum = 0·8118. Maximum Velocity = 2406·3 ft. per min.

No. 2. Mean Position 0·721 r. from centre. Ratio of Mean to Maximum = 0·79. Maximum Velocity = 2472·6 ft. per min.

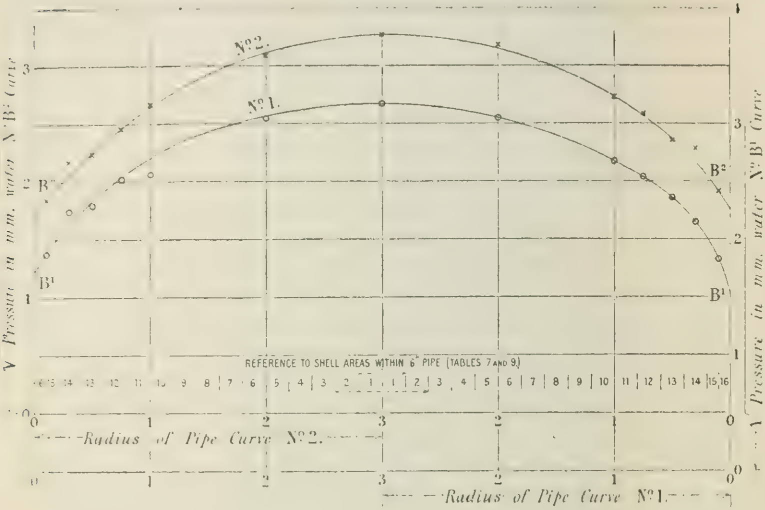
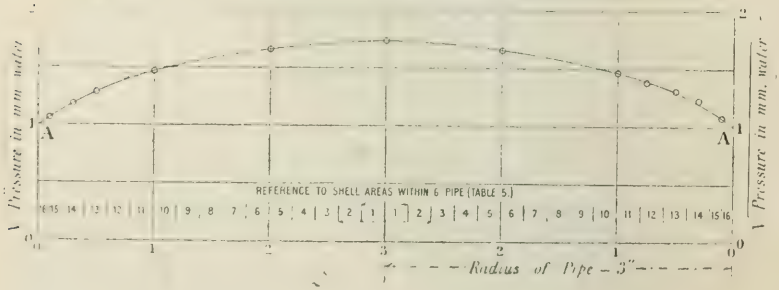


FIG. 9.

Distribution of Velocity Curves for 6-inch pipe attached to Gasholder at a low velocity. 8 *Jan.* 1903.

Mean Position = 0·737 r. from centre. Ratio of Mean to Maximum = 0·8066. Maximum Velocity = 1319·4 ft. per min.



APPENDIX IV.

Investigation of the Law connecting Velocity of Air and Gauge Indications. Fig. 2 (page 254).

It happened fortunately that a considerable length of wrought-iron pipe 0·2 inch thick in the walls was available for the experiments. Each length of pipe was very slightly conical so that the sections fitted into each other. The direction of the air current was from the larger to the smaller end of each section.

Distance from firing point where puff of smoke is produced to the open end of the pipe where it is observed 108 feet 10 inches = 3317·1 cm.

Internal diameter of main pipe, 20·8 inches = 52·75 cm.

Internal diameter of wooden connectors, 20·8 inches = 52·75 cm.

Length of experimental section, 14 feet 6 inches = 442 cm.

Internal diameter of experimental pipe, 21·4 inches = 54·21 cm.

Area of section of main pipe, 2·352 square feet = 2.185 cm^2.

Area of section experimental pipe, 2·484 square feet = 2.308 cm^2.

Time Measurements.—A puff of smoke was introduced into the pipe by exploding electrically a minute charge of gun-cotton fluff, picrate of potash, and meal powder. The charges were not weighed, but less than one gram of explosive was used in each case. The exploders were simply thin platinum or copper wire fuses; the wire was covered with the explosive and the latter kept in position by a drop of collodion. The fuses were well dried so as to give prompt ignition. It was found that an observer placed at the delivery end of the pipe and looking up it easily saw the flash of the explosion.

The time measurement was made by means of a chronograph consisting of a smoked glass sheet mounted on a mono-rail carriage. Time was marked on the smoked glass by a scriber supplied with intermittent current from a torsion pendulum which itself was timed by a stop-watch compared for twenty-four hours with standard time and found to have a negligible rate. The comparison with the standard time was made when the centre second and stop minute hand were in gear. The epoch of the explosion was registered by the observer at the pipe, who depressed a key working an electro-magnetic scriber touching the glass plate of the chronograph.

When the smoke began to emerge from the pipe the key was again depressed, and again when the smoke just cleared off.

At first the firing of the charge was registered automatically, and the time constants of the fuses and of the observer ascertained and allowed for. After it was found that the flash could be seen through the whole length of pipe, the method above described was adopted as both a simplification and an improvement, as it undoubtedly was. The time constants were practically eliminated by this procedure.

The plates with the records were measured by two observers, and, in the case of any discrepancy appearing, they were remeasured. This is a very essential precaution in chronograph work, for it is much easier to make a mistake in counting the time signals than is generally supposed. The torsion pendulum gave contact signals at intervals of 0·365 second. The plate was about 2 feet long, and was run at such a rate as to bring the signals sent by the observer at the tube just within this distance. There are many advantages in using a torsion rather than an ordinary pendulum for giving signals of short period.

Reduction of Observations.—The anemometer tubes (being placed in the observing part of the pipe system which is of larger diameter than the rest of the pipe) are exposed to the action of a current of air moving with rather less velocity than that of the current calculated from the time signals and the overall length of the pipe. A correction, however, is easily found for this on the assumption that the stream has had time to accommodate itself to the larger pipe. Since the latter is 14 feet 6 inches long with a diameter of about 21·4 inches, and the instruments are placed at the middle of its length, this condition may be considered to be satisfied.

In this case let v be the observed velocity, that is, total length between firing and observation point divided by the time of passage. If the velocity in the wider pipe be u we have the relation

$$u = v \times 0{\cdot}9539$$

a correction to be applied to all velocities examined by this apparatus.

TABLE 10.—*Showing a set of observations with Fletcher gauge A.*

	Barometer 764·4 mm. at 0° C. and at sea-level. Temperature of air in pipe 21°·25° C. Date, 4 Oct. 1901.					
Least time in seconds (or maximum velocity).	5·7[illegible]	5·707	5·723	5·798	5·928	6·124
Mean time in seconds = (Max. + Min.)/2	6·372	6·358	6·279	6·404	6·005	6·370
Greatest and least times in oscillations of time marker.	{16·[illegible] 16·[illegible]}	{15·[illegible] 16·[illegible]}	{15·772 16·[illegible]}	{16·[illegible] 15·[illegible]}	{15·[illegible] 18·[illegible]}	{15·981 16·[illegible]}
B.'s measurement of plates. Time for last appearance of smoke in oscillations.	16·997	16·[illegible]	16·[illegible]	16·[illegible]	18·[illegible]	16·[illegible]
Ditto. Time of passage for first appearance of smoke in oscillations.	16·104	15·8[illegible]	15·772	16·[illegible]	15·872	15·981
W.'s measurement of Plate. Time for last appearance of smoke in oscillations.	16·207	16·[illegible]	16·[illegible]	16·525	18·[illegible]	16·482
Ditto. Time of passage for first appearance of smoke in oscillations.	16·093	15·833	15·772	16·017	15·819	15·981
Pressure in millimetres of water.	5·86	5·86	4·61	5·85	5·85	5·84
Anemometer reading micrometer millimetres.	[illegible]	[illegible]	21·40	[illegible]	[illegible]	[illegible]
Engine revs. per min.	97	97	101	100	100	101
Reference No. of shot.	1	2	3	4	5	6

Measurement of Velocity of Air in Pipes by means of Smoke Signals.—In order that an idea may be obtained as to the constancy of the observations a typical set of readings and reductions is given in Table 10 (page 289), without however including the final corrections for increased diameter of experimental tube, correct period of time marker, &c. The observations were made with the standard pressure and suction combination A, that is, a standard Fletcher gauge. This gauge was placed at the centre of the pipe as nearly as the finite dimensions of the tube permitted. The diameter of the experimental pipe was 21·4 inches.

In Table 11 (page 291) are collected together all the experimental results obtained with the apparatus described (*i.e.* the standard Fletcher gauge A), which results involved a direct determination of the velocity by means of the smoke puffs and chronograph. All the results in Table 11 have been corrected for instrumental peculiarities, but are not reduced to a standard temperature and pressure. The air current was, as a rule, a little warmer at the entry than at the exit end, being drawn by the fan from a chamber slightly warmed to facilitate a manufacturing process. The details of each measurement were similar in all respects to the details of the measurements given in Table 10.

The results tabulated in Table 11 appear as a curve AA on Fig. 2 (page 254), and we shall here confine our attention to the experimental curve of maximum velocities and to a calculated curve passing through a convenient point.

Plotted for $KV^2 = P$.

The author has not pursued this matter in order to find what formula, if any, will better represent the observations, because, as stated above, any slight change in the side-gauge affects the results.

The figures contained in Table 11, however, are sufficient to enable an approximate idea as to the delivery of air to be obtained but before this complex matter is considered, it will be more convenient to give an account of the experiments made with the facing-gauge only.

TABLE 11.

Showing Anemometer Readings and Velocities measured directly.
Fletcher Gauge A used throughout.

	Anemometer Readings in mm. water	Maximum Velocity Feet per minute.	Mean Velocity Feet per minute	Ratio Mean Velocity / Maximum Velocity	Anemometer Readings in mm. water	Maximum Velocity Feet per minute	Mean Velocity Feet per minute	Ratio Mean Velocity / Maximum Velocity	
Barometer 753·7 Temp. 12·2° C.	7·48	1411	1262	0·8908	3·20	1072	945·4	0·882	Barometer 761·5 mm Temperature 12·4° C.
	6·88	1375	1283	0·9340	2·68	951·2	845·4	0·891	
	7·22	1388	1261	0·9288	3·08	945·8	833·8	0·881	
	7·34	1410	1314	0·9270	3·04	978·0	875·6	0·891	
	7·70	1414	1298	0·9175					
	7·26	1360	1233	0·9067	3·04	952·6	870·8	0·914	
					3·12	990·2	876·6	0·883	
Barometer 764·2, Temp. 24·5° C.	5·25	1211	1138	0·9402					Barometer 761·1 Temperature 22° C.
	5·23	1207	1125	0·9320	2·86	1070	974·0	0·910	
	5·05	1228	1126	0·9060	2·86	1076	963·1	0·892	
	5·05	1166	1075	0·9156	4·01	1082	979·6	0·905	
	4·53	1158	1060	0·9110	3·85	1065	959·4	0·901	
	5·11	1198	1087	0·907	3·83	1078	1008	0·935	
					3·84	1068	962·6	0·902	
Barometer 758·5 Temp. 22° C.	9·56	1718	1521	0·8855	Fig. 3 (page 234).				
	9·64	1615	1462	0·907					
	9·74	1717	1489	0·867					
	9·29	1550	1434	0·925					
	8·55	1397	1233	0·882					
	9·80	1623	1477	0·910					

TABLE 12.

Showing relation between measured velocity of an air stream and pressure difference due to facing-gauge only, i.e. a Pitot tube.

Curves C, D, Fig. 2 (page 254).

Date 1901.	Engine revolutions per minute.	Gauge pressure in mm. water.	Greatest time in seconds.	Least time in seconds.	Mean time in seconds.	Maximum velocity in feet per minute.	Mean velocity in feet per minute.	$\frac{\text{Mean velocity}}{\text{Maximum velocity}}$
20 Nov.	90	1·66	7·815	6·344	7·094	9816	8778	0·894
..	90	1·64	7·627	6·514	7·070	9558	8808	0·9215
..	92	1·70	7·48	6·33	6·905	9840	9018	0·9165
,,	92	1·75	7·061	6·170	6·616	1009·2	9414	0·933
..	92	1·76	6·277	6·141	6·209	1014·0	1003	0·989
..	92	1·71	7·189	6·083	6·636	1023·6	938·4	0·917
21 Nov.	114	2·35	6·124	5·164	5·645	1206	1103	0·9146
..	112	2·35	6·295	5·231	5·756	1190	1081·8	0·909
..	134	3·54	5·021	4·213	4·617	1478	1349	0·913*
..	144	3·76	4·95	4·26	4·603	1461	1353	0·926
..	144	3·77	4·736	4·131	4·434	1508	1405	0·9316
..	168	4·17	4·744	3·955	4·352	1574	1431	0·971
23 Nov.	75	1·19	8·735	—	8·047	846·3	774	0·915
..	75	1·19	8·931	7·313	8·122	851·6	766·8	0·9002
..	62	0·91	10·154	8·635	9·391	721·1	663	0·9195
,,	126	3·21	5·331	4·584	4·957	135·9	1256	0·924

* Engine very unsteady.

The observations of pressure difference for 23 Nov., when corrected for change of temperature and pressure, i.e. reduced to 16° C. and 758 mm. so as to compare with other observations, are as follows. The air is taken throughout as half saturated :—

1·19 mm. becomes 1·145 mm.
0·91 ,, ,, 0·85 ,,
3·21 ,, ,, 3·09 ,,

Relation between Velocity and Pitot-Tube Pressure.—In the observations for velocity the same apparatus was used as in the former series, but the measurements are on the whole better, because more experience in manipulation had been obtained.

The facing-gauge employed was the facing member of the standard Fletcher gauge A, which was examined as to the condition of the operative end of the pipe, and this was found to be perfectly smooth and square. A flanged gauge of usual construction was employed in connection with this. It was thrust to the centre of the pipe carrying the air so as to be exposed to the maximum velocity of the current. The series of observations finally reduced extended over three days; on the first two days the barometer stood at 759·2 and 756·5 mm.; these are for the present purpose taken as being 760·0; on the third day the barometer was 776·3. The temperatures were on the first two days 17·2° and 16·52° C. respectively, and on the third day the temperature was 11·6° C.

The results recorded in Table 12 were treated geometrically, Curves C, D, Fig. 2 (page 254), and found to be practically in complete accordance with the formula

$$V = 0{\cdot}9757 \sqrt{\frac{2P}{\rho}},$$

as may be seen from the curve of maximum velocities.

The pressure was 760 mm. of mercury and the air was taken as half saturated at 16° C., with a density of 0·001213 grammes per cubic centimetre. The working formula, as referring to air half saturated with water vapour at 16° C. giving the linear velocity in feet per minute, is

$$V = 771 \sqrt{\text{Pressure in mm. of water}},$$

or

$$V = 752 \sqrt{\text{Pressure in mm. water}} \text{ (feet per minute)}$$

referring to air dry under standard conditions.

Comparison can now be made of the curve for the combined effect of the pressure and suction tubes with the effect due to the former alone. It will be seen that the two effects are nearly equal, how nearly is shown in the following Table 13:—

TABLE 13.

Pressure due to facing-gauge only.	Pressure as given by Fletcher-combination minus facing-gauge pressure.
Water. mm.	Water. mm.
1·07	1·14
1·35	1·37
1·68	1·69
2·03	2·29
2·42	2·64
2·83	3·27
3·29	3·96
3·77	4·76
4·32	5·53

The fact that the combined action of the pressure and suction is nearly double that of the pressure alone tempted the author to examine this matter more closely. The observations hitherto made had been obtained slowly, and it seemed unlikely that very good comparative results could come from observations spread over such a long period (two months) of time. Some trials were therefore arranged, in which one observer kept the engine as steady as possible and the other took alternate readings by the Fletcher A gauge, and the pressure member of Fletcher B opposed by the flange-gauge placed against the inner wall of the pipe. Four sets of observations taken alternately with each combination, gave, with the engine making 43 revolutions per minute :—

Fletcher gauge A . . . 0·565 mm. of water = 100 units.
Facing-gauge B . . . 0·365 ,, = 64·6 ,,

The facing parts of A and B gave the same readings exactly.

A trial was then made with the tubes supplied by Messrs. Mawson and Swan, which were evidently carefully made and no doubt similar to the sets supplied to most Chemical Works thirty years ago. Results are as follows, the engine being kept at 120 revolutions per minute :—

1.	Fletcher gauge—Swan type	5 observations.—Mean pressure tube difference	6·[illegible]
2.	Swan facing-gauge—Standard flange-gauge	5 — — —	3·144
3.	Fletcher—Swan type	5 — —	6·[illegible]
4.	Swan facing-gauge—Standard flange-gauge	5 — — —	3·[illegible]
5.	Fletcher—Swan type, another tube	5 — —	6·175
6.	Swan facing gauge—Standard flange-gauge	4 — — —	3·144
7.	Fletcher—Swan type as in 5	5 — —	6·134
8.	Swan facing-gauge—Standard flange-gauge	4 — — —	3·[illegible]
9.	Fletcher A	8 — — —	6·862
10.	Facing-gauge of Fletcher A and standard flange-gauge	7 — —	3·094

Averaging the above observations, which have been set out in the order in which they were made, so as to get over engine unsteadiness, we have :—

Pressure difference—Fletcher Swan	1st pair	6·718[illegible] mm.	= 100	parts
Swan facing and Standard flange		3·144 ,,	= [illegible]	,,
Fletcher Swan	2nd pair	6·102 ,,	= 100	,,
Swan facing and Standard flange		3·051 ,,	= [illegible]	,,
Average of all Fletcher Swan		6·[illegible] ,,	= 100	,,
,, ,, Swan Pressure and Flange gauge		3·102 ,,	= [illegible]	,,
Pressure difference, Standard Fletcher A		6·862 ,,	= 100	,,
Pressure difference facing-gauge Fletcher A and flange-gauge		3·094 ,,	= [illegible]	,,

The velocity of air in the centre of the pipe is in all the above experiments, by formula, 1,258 feet per minute.

APPENDIX V.

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Discussion.

The PRESIDENT asked the Members to indicate by their applause their appreciation of the fascinating and valuable Paper which Mr Threlfall had given.

The resolution of thanks was carried by acclamation.

Dr. R. T. GLAZEBROOK said that he was glad to say a few words on the points that had been raised by the author, more especially as the Pitot tube had, during the past year and a half, been the object of very considerable investigations at the National Physical Laboratory, and their results had borne out he thought, in a very striking manner, those that had been obtained by the author. Their problem at the National Physical Laboratory, which was described at a meeting of the Institution of Civil Engineers last December in a Paper on the Resistance of Plain Surfaces in a uniform Current of Air, was a somewhat different one, because they desired in the first place to produce a uniform current of air through a pipe, then to measure the velocity of that current, and had used the Pitot tube, as the author had done, as a means of measuring the velocity. They had therefore to establish the law connecting the velocity and pressure for the Pitot tube that was used.

As the author had found, the law came out to be what they might have expected it by theory. He would like to refer to the theory in a moment. The velocity was $K\sqrt{\frac{2p}{\rho}}$, where K was a constant, which, if the conditions assumed in the theory held accurately, would be unity. Mr. Threlfall, he understood, found the value of K was 0·97 instead of unity, whereas the value that Dr Stanton obtained for K in his experiments was rather greater, 1·03. He thought, however, there was sufficient agreement between those two figures, obtained with entirely different forms of apparatus, to show that the method of measuring velocities up to something like 3,000 feet a minute by means of the Pitot tube, was one which might safely be adopted. He ought to have said that the tube used at the National Physical Laboratory would not have been at all

(Dr. R. T. Glazebrook.)

suitable for Mr. Threlfall's experiments. They worked with a pipe as large as the author's, 25 inches in diameter, but they had none of the difficulties to meet that the author had in using producer-gas. They used dry, clean air, and therefore it was possible to keep the Pitot tube extremely small, and to measure the static pressure in the close neighbourhood of the point at which the velocity pressure was measured. He thought, therefore, that probably some portion of the difference would be accounted for, by the fact that they were measuring the static pressure close up to the point at which they were measuring the velocity head, and Mr. Threlfall for his purposes was measuring it at the side of the tube, which would, he believed, make a difference in the direction indicated by the two numbers. If the author's measurement had been taken in the same position as theirs, those two numbers would probably have agreed much more closely.

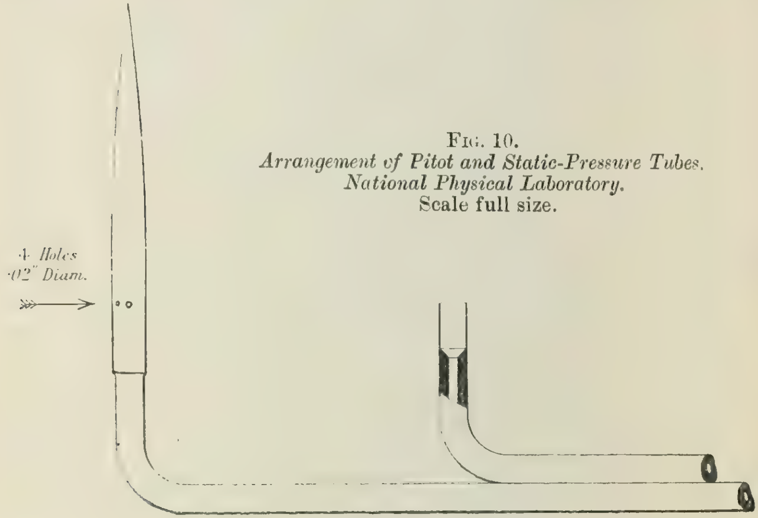


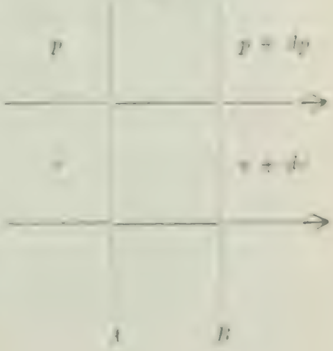
Fig. 10.
Arrangement of Pitot and Static-Pressure Tubes.
National Physical Laboratory.
Scale full size.

The Pitot tube, as used in the Laboratory, was shown in Fig. 10. The static-pressure tube terminated in a very fine point closed at the end. The tube was placed with its length parallel to the flow, and at some distance from the end it was pierced by four small holes about 0·02 inch in diameter. The pressure tube was shown at one side; it had a small cup-like mouth on which the stream impinged. The tubes were connected to the gauge, and it was thus possible to measure the velocity of the static pressure in very close proximity to the velocity head. He was speaking from memory at the present moment, but he believed the diameter of the tube, instead of being $\frac{1}{2}$ inch, was something like $\frac{1}{16}$ inch, and the sides of the tube were thin. Under those circumstances he thought the members might take it as proved that the fundamental formula $V = K\sqrt{\left(\frac{2p}{\rho}\right)}$ held, the value K being very nearly unity. He was a little sorry that the author had put his result in the form he did, in the statement that half the momentum was destroyed. He did not think that was quite the best way to look at the theoretical result, for this reason: they were concerned with the fluid pressure over a definite area.

Now Mr. Threlfall supposed there was a series of molecules impinging on the area, having their velocity destroyed, and from that point of view he obtained his equation without the 2 in the numerator. But in reality they were dealing, not with a series of independent molecules, but with a continuous fluid, and the effect of the pressure would be propagated backwards throughout the whole of the fluid; thus it was not sufficient as a theoretical account of what was going on to deal with a series of isolated independent molecules.

If, instead of working as the author had done, we considered the fluid between two parallel planes A and B, Fig. 11, drawn at right angles to the direction of the flow, such that p, v were the pressure and velocity over A, $p + dp$ and $v + dv$ the corresponding pressure and velocity over B. Then, dealing with the fluid crossing unit area of these planes, the gain of momentum per unit time is $\rho v dv$, where ρ is the density, and the force producing this is $-dp$.

Fig. 11.



Hence we have as the equation connecting these—

$$\rho v dv + dp = 0.$$

Whence integrating

$$\frac{1}{2}\rho v^2 + p = \text{a constant.}$$

Taking then this equation from a position in the fluid at which the pressure and velocity are p_0 and v_0 to one in which they are p_1 and v_1, we have

$$p_1 + \frac{1}{2}\rho v_1^2 = p_0 + \frac{1}{2}\rho v_0^2$$

And if we suppose that in the second position, corresponding to the mouth of the gauge, the velocity v_1 is zero, one found the result

$$p_1 - p_0 = \frac{1}{2}\rho v_0^2.$$

In this way the $\frac{1}{2}$ that the author found he had to introduce, in order to make his theory agree with his experiment, appeared, the fact being that, of course, one did not suddenly destroy at one point all the momentum, but there was, starting from the mouth of the gauge and going back, a decreasing pressure and an increasing velocity. That, however, was a small theoretical point. The real matter he wished to bring forward was the agreement between Dr. Stanton's experiments and those of the author with regard to the fundamental formula, and to emphasise the fact that for many purposes the Pitot tube could be used most satisfactorily. He thought the author was very much to be congratulated on the results he had laid before the Institution in the Paper, and especially on the very interesting gauge which was on exhibition, and the method described in the Paper of integrating the Pitot tube results.

Professor W. CAWTHORNE UNWIN thought the author had certainly accomplished a very original and striking piece of work in measuring the frictional work of a dynamo by means of an air current, in doing which he had been led into the research which he had now brought forward before the Institution in regard to the means of measuring the volume of flow of a gas or air through a pipe. It was curious that it was in 1732, nearly 200 years ago, that Pitot described to the Academy of Sciences the Pitot tube. Two hundred years ago Pitot used his tube in an exceedingly rational form.

A triangular block of wood with its edge facing the stream carried the two Pitot tubes at the back, one having its mouth parallel to the stream and the other, bent at right angles and brought to the triangular edge, having its mouth facing the stream. Pitot said that that difference of level in the tubes must be the head due to the velocity. What Pitot said at the time was really so good that he (Professor Unwin) did not think it could be improved upon now; it was "The general level of the current is shown by the rise of water in the straight tube, while the height of water in the bent tube becomes a measure of the force of the stream. The difference between these heights will therefore be the height due to the velocity." * Several hydraulicians in France used the Pitot tube after that, and tried to improve it, but he (Professor Unwin) thought they spoilt it, and it got a bad name; and it was not till Darcy took up the Pitot tube again that it became a really valuable instrument of precision.

Darcy, and after him Bazin, carried out an enormous series of researches on flow in pipes of various shapes, and in streams of various shapes and flow over weirs, with an accuracy which he thought incontestable. The whole of the results depended on the use of the Pitot tube. All that Darcy did with the Pitot tube, except for mere arrangements of convenience, was to show that if the Pitot tube was to be made accurate it must be made so that it disturbed the current as little as possible, and therefore he used very much what Dr. Glazebrook had been using at Bushy, namely very small tubes with very small apertures.

The only improvement in the Darcy tube which was of importance was the reducing of the size of the tubes to a very small size, so as to disturb the current in the neighbourhood of their

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* "Encyclopædia Metropolitana," 1829.

(Professor W. Cawthorne Unwin.)

mouths as little as possible. He did not think Mr. Threlfall was very well acquainted with the vast amount of work which had been done by Darcy and Bazin. There was a second Pitot tube constructed by Bazin himself, and experimented on very carefully, which he used for gauging the velocity in streams. He calibrated the tube by three wholly different methods, and obtained for the coefficient of the instrument the values 0·993, 1·006, and 1·034. Allowing for the probable error of the different methods, he concluded that the coefficient could not differ sensibly from unity. These values were much the same as those obtained by Dr. Glazebrook and Mr. Threlfall.

FIG. 12.

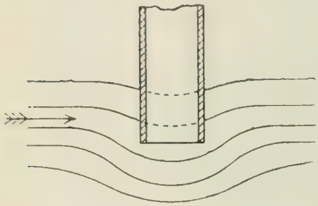
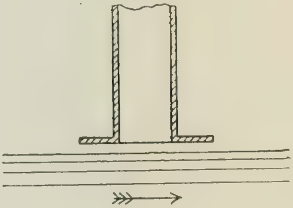


FIG. 13.



It so happened that a few years ago Mr. Gilbert and Mr. Heenan were making experiments on fans. Mr. Gilbert came to him with regard to the measurement of the velocity, and he (Professor Unwin) suggested the use of the Pitot tube. Mr. Gilbert came back to him afterwards, and told him that irregular results were being obtained which he could not quite understand. Tubes which were not of a very small size were being used, and he (Professor Unwin) thought at once that probably the difficulty arose from the suction effect on the tube which gave the statical pressure, about which so much was said in the Paper. He then remembered reading many years ago that very accurate results had been obtained with forms of Pitot tubes, which were recorded by Dupré in his treatise, "Théorie Mécanique de la Chaleur" (1869). Dupré had done this rather ingenious thing:—He produced a steady current of air and placed in it an open-mouthed tube which could be placed at any angle to the current. The pressure in the tube was measured at different inclinations. When the tube was at right angles to the current he found a suction effect. His tube was not a very small one, and the reason of the suction effect was obvious. The tube disturbed the current, and the stream lines were curved as in Fig. 12. Now wherever stream lines were curved, the pressure diminished towards the centre of curvature. Dupré found that if a disc was placed at the mouth of the tube as in Fig. 13, the true statical pressure of the stream of air was measured. Dupré had not given the explanation, but it was no doubt that the curvature of the stream lines was prevented. He (Professor Unwin) suggested to Mr. Gilbert to use this disc on the tube, and the difficulty in the fan experiments disappeared. Those experiments were made with air, and showed that the Pitot-tube arrangement was just as suitable for a current of fluid air as for a current of fluid water, a thing which it was hardly necessary to prove.

He thought the author, in the earlier part of the Paper, had cumbered himself with a great many irrelevant considerations about viscosity and eddy motion, and so on, and that some of the statements were very curiously doubtful. They did not affect at all the results, but only the author's reasoning about them. There was the quite extraordinary statement that his theory of the momentum of the stream against the mouth of the Pitot tube involved that the gas should be annihilated (page 246). "In practice, however, the gas cannot be annihilated when it comes to rest; it has to be pushed out sideways, and the force to do this must come from the gas itself." That was a very curious way of putting the theory of the Pitot tube, and did not in any way correspond to the actual facts. Take a simpler case which could be treated exactly. A jet of section w and velocity v strikes a fixed plane, Fig 14 (page 304), and is deviated at right angles in all directions. The quantity of fluid impinging per second is wv, its weight is Gwv, where G is the weight of a cubic foot of water. The whole of the momentum in the direction of the jet is destroyed, and therefore the pressure on the plane is $P = \frac{G}{g} wv^2$. This was exactly the result which Mr. Threlfall got for the pressure on the mouth of the Pitot tube. But on the plane the pressure was distributed over an area much greater than w, the mean intensity of pressure was much less than P/w and the greatest intensity of pressure at the centre of the area struck never exceeded $G\frac{v^2}{2g}$ in lbs. per square foot, or $\frac{v^2}{2g}$ in feet of water. It could not exceed this, or there would be reflux towards the jet.

Many years ago Mr. Froude showed an experiment arranged thus:—Water was maintained in vessel A, Fig. 15, at the level O O, and discharged across an air-gap from A into B. The level in B rose till it reached the level O O, but never higher. When the level was nearly the same in A and B there was an oscillating discharge, sometimes from A and sometimes from B, and a lamina formed in the air-gap. This showed that the pressure on the mouth of the tube leading into B should reach but could not exceed $\frac{v^2}{2g}$. The case was very similar to the Pitot tube, and proved that, except for small disturbances produced by the tube itself, the formula for the Pitot tube should be $h = \frac{v^2}{2g}$ with a coefficient unity.

FIG. 14.

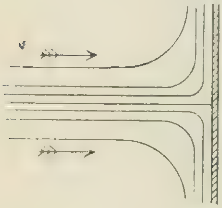
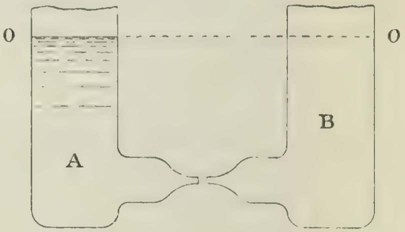


FIG. 15.



The measurement of flow of air and gas in pipes was likely to be important in connection with producer-gas, and therefore he might make two suggestions:—(1) It was not at all clear that a Venturi meter could not be used for measuring gas as well as water, and it would be much simpler and more reliable than the Pitot tube. (2) If the Venturi meter could not be used, it still would be desirable to place the Pitot tube in the throat of a converging and diverging tube formed like a Venturi meter. The irregularities in the curves of distribution of velocity shown in Mr. Threlfall's diagrams were no doubt due to actions beyond the part of the pipe in which the Pitot tube was placed. These irregularities would be reduced and at the same time the pressure heads to be measured would be increased easily sixteen or more times, and thus would make the pressure measurement much more convenient. One difficulty would arise in Mr. Threlfall's method, and that was that to interpret the results the density of the gas must be accurately known.

He was surprised that the author stated he did not know that the position of the circle of mean velocity in a pipe found by Darcy was more than a theoretical deduction. It was, of course, a purely observational result. That Darcy fitted an empirical equation to his observations, and deduced the radius of mean velocity from that, did not make the result a theoretical one. Darcy found the radius of the circle of mean velocity to be 0·689 of the radius of the pipe, and the author found it to be 0·775 of the radius of the pipe (or 0·725 and 0·757, page 285). Though the figures looked discrepant, it must be remembered that what was really determined in the experiments was not the radius of mean velocity itself but merely the difference of velocity at points near the mean radius, and this was a very small quantity. Further, the author appeared not to be acquainted with the later research of Bazin (1897) in which the radius of mean velocity was found at 0·74 of the radius of the pipe. It did not appear that the velocity of flow affected the position of the circle of mean velocity, but in all probability the roughness of the pipe did affect it.

Mr. Henry Lea, Member of Council, said he had not very much to say, because the subject of measuring the velocity of air in pipes had not occupied any material amount of his attention. It seemed to him that one very important point of the Paper was that the author had made a recent and up-to-date confirmation of the accuracy of so simple an apparatus as the Pitot tube. Its simplicity seemed to him to leave nothing to be desired, but its indications were of so minute a character that, unless one had the means of measuring very accurately the indications of the tube, the tube was not likely to be, at any rate in measuring

(Mr. Henry Lea.)

the flow of gases, of much value. In that connection the additional value of the author's investigations, in which he devised the means for measuring with extreme accuracy the indications of the Pitot tube, were manifest. When one compared the reading of the water-level in a glass tube with the readings obtained from the micrometer gauges used by the author, a comparison was being made between two things which were, one might say, miles apart, and of which the first would have been of no use in dealing with the indications of the Pitot tube, whereas the second, giving a reliability of something like three parts in a thousand, enabled one to ascertain the indications with an accuracy which left nothing to be desired.

He would like to ask one or two questions. The author described (page 269) a meter which appeared to be a combination of displacement apparatus and electrical apparatus. He confessed that he could not, on reading the description, understand how the difference of the water-level varied the amount of the rate of the electric current which was used as a medium for measuring the quantity of gas passing through the tube. The next question he wished to ask was, whether the author had ever tried the application of the Pitot tube to the measurement of the flow of steam through a pipe. In many cases one ascertained the amount of steam used by a steam-engine by condensing the steam in a surface condenser and weighing the water that came therefrom; but there were thousands of non-condensing engines in use in which nothing of the kind could be done, and the only method which could be adopted then was to measure the feed-water pumped into the boiler. But there were very many cases in which the steam from the boiler did other work besides driving the engine; therefore, unless all the other work was stopped, nothing like a correct measurement of the steam passing to the engine could be obtained. If such a simple thing as the Pitot tube could be applied to the steam-pipe which was taking steam to the engine, it seemed to him it would constitute a most valuable means of ascertaining what that engine was using in steam per hour.

He wished to ask how the author made quite sure that there were no eddies in the gas in the pipe which he used. He supposed it might be presumed that the fact that the anemometer indications agreed within, he thought, 1½ per cent., or something of that kind, with the Pitot-tube indications, that if there were any eddies they did not materially affect the results. More probably, however, on account of the very straightforward arrangements of the tube, there were no eddies, or next to none. But he could conceive that unless a perfectly straight tube of great length was adopted, eddies might be obtained which would seriously interfere with his observations. He would like to know whether the author had met with any instances of that kind, and if so, in what manner he avoided the errors which would result from material amounts of eddies.

Mr. Threlfall, in reply to Dr. Glazebrook's remarks (page 297), said he wished Dr. Glazebrook and his staff had carried out their investigations two or three years ago, because it would have saved him a great deal of work, and he would have been enabled to measure producer-gas rather sooner. With regard to the formula that Dr. Glazebrook had quoted, he noted that the constant in his (the author's) formula was 0·97 and in Dr. Stanton's formula was 1·03. A good deal of the difference was, as Dr. Glazebrook stated, due to the fact that he (the author) generally placed his side-gauge at the side of the tube, and not where he ought theoretically to have placed it; but some of it was also due to the fact that a flange-gauge did give some little suction, and Dr. Stanton's torpedo gauge, with little tiny holes in it, probably did not give any suction at all. Bearing that in mind, with the results on a 6-inch pipe mentioned in the Paper, he thought his figure would come up to about 0·984, which was not very far from Dr. Stanton's 1·03. It looked almost as if Dr. Stanton had no suction, but that on the other hand he had failed to get the full pressure in the Pitot tube, in this resembling Darcy. He was not surprised that Dr. Glazebrook smiled at his hydrodynamics which, considered as hydrodynamics, were no doubt rather feeble. But the difference was that Dr. Glazebrook, like other people who knew hydrodynamics properly, always thought of the motion of an element of fluid; but he (the

(Mr. Threlfall.)

author) started the investigation by considering the resistance of a lamina, in which the results were stated in the momentum loss corresponding to the dimensions of that lamina. He got into that habit, and never got out of it, but it led to exactly the same result. The formulæ obtained were quite different to begin with—he was quite frightened when he discovered that there were such differences—but when he considered the volume of fluid and worked it out just as Dr. Glazebrook had done, he obtained the same result as he had previously obtained. It was only a question as to whether one thought of a volume of fluid, or whether one thought of the area of the surface of the obstacle.

Professor Unwin's scholarly remarks had been exceedingly interesting to him. He had never been able to discover where Pitot described his work of 1732, and if Professor Unwin could give him that reference he would be very much obliged. He was afraid he could not plead guilty to being unacquainted with the work of Darcy. He studied Darcy's work extremely carefully, and on two separate occasions made complete abstracts of that part of the investigation dealing with the Pitot tube and velocity distribution. But he pleaded guilty to being ignorant of Bazin's work. Bazin's work in regard to gauging was of course well known to him, but he had not looked him up in connection with the testing of Pitot tubes, and should be glad to have the reference. He knew it was absurd for him to set up his opinion against Professor Unwin's, but he spoke advisedly when he said that he thought Darcy's result as to the radius of mean velocity was, to some extent, theoretical, and he was prepared to adhere to that position. It was the result of a mathematical discussion of the experimental results of smooth uniform circular pipes of uniform slope, and any attempt to apply the formula to other conditions was based on some assumption or other. Professor Unwin had appeared to attribute to him (the author) some general statement as to the radius of mean velocity. This however was far from the author's intention, for his view was that in practical cases of gas measurement there was no such thing as a circle of mean velocity with a radius which could be assigned beforehand. The values seemed to congregate about the number 0·77, but the distribution varied so much that any general statement was out of the question.

With regard to the results given by Professor Unwin as to the constant obtained by Darcy, namely, the difference between 0·977 and 1·03, he formed an exceedingly definite opinion that these figures implicitly contained a claim for accuracy perfectly unjustified by the apparatus which Darcy had at his disposal. No doubt the figures quoted appeared as the average of all Darcy's observations, but they were simply obtained by taking advantage of a vast number of observations, his apparatus being incapable of giving results of the precision implied. Professor Unwin had anticipated a question he would like to have asked, namely, how he (Professor Unwin) came to invent the flange-gauge. Professor Unwin had stated that it was M. Dupré's invention, and it certainly was an extremely ingenious one. But there still remained for somebody to explain why it was that the suction in an open tube, with infinitely thin walls as opposed to the flange-gauge, should be practically equal to the Pitot-tube pressure. Professor Unwin's explanation merely amounted to a restatement of the facts in such a way that they were brought into line with the general theorems of hydrodynamics. In regard to Professor Unwin's criticism of his use of the idea of the annihilation of the gas, he could only refer to the text, from which it would appear that he (the author) had been misquoted. No doubt he had somehow failed to make his meaning clear. It had been suggested by Professor Unwin that the Venturi meter might be used: the Venturi meter was used in water, and it no doubt might be used for gas. There were many ways in which one might make a meter, now one knew that the Pitot tube gave reliable results, by which the meter could be calibrated. With regard to making the Venturi pipe part of a gas-main: when one had a main 4 or 5 feet in diameter, one liked to interfere with it as little as possible; such a big main was extremely expensive, and to make a Venturi contraction on such a scale would also be very expensive. He did not know how he came to give the impression—as he appeared to have given it—that he thought it was possible for gas to be annihilated. His view was, that if the gas had been annihilated, then the momentum loss

(Mr. Threlfall.)

would be so and so, and the pressure set up so and so; but as it was not, he had to look round and see what the other conditions were: and from his way of looking at it the pressure set up in the Pitot tube could not be greater than the pressure head giving an equal velocity of efflux. While dealing with the question of the Venturi meter, he would like to be allowed to ask Professor Unwin a question. He had heard a statement to this effect—he did not know with what truth, and he could not trace the source of the remark, except that he knew it came from a reliable source—that the Romans were acquainted with the Venturi mouth-piece, and that certain classes paid for water on the basis of so much for a connection. They were sufficiently well posted to be able to put on a Venturi mouthpiece and steal the water by taking advantage of the properties of the Venturi mouthpiece.

With regard to the density of producer gas, in practice for a given producer that did not vary appreciably. With regard to the difference of radii of mean velocity as given by his observations and those of Darcy, he could say that he had tried his in all ways, and that the difference was not to be explained, so far as his observations were concerned, by observational error. He began by supposing he might be in error, but he had tested his results in every way, and he was certain of them. He did not now expect to get the same results as Darcy. He had never examined a pipe in which the conditions corresponding to a uniform slope had been sufficiently satisfied, nor had the condition of getting a uniform flow at the inlet, or, in the alternative, an infinitely long pipe, been sufficiently satisfied. Professor Unwin's remarks on matters of theory were based on the hydrodynamics of frictionless fluids; no doubt the author's treatment was lamentably defective, but it had the merit of not taking for granted that producer gas would behave so nearly like a frictionless fluid, that calculations involving large sums of money could be safely based on that hypothesis.

In reply to Mr. Lea, he was sorry that he did not make the meter clear, but he would explain it if he wished him to do so. The way in which the apparatus worked was as follows: the current went through the coils of a dynamometer. When the arm of the dynamometer was pulled downwards by the Pitot-tube pressure, it made a contact which operated various mechanisms, and let more current through the balance to oppose the Pitot-tube pressure. His experiments on steam were not yet ripe, but he might mention that there was an extra difficulty in that the density of steam was of course variable with the pressure. In the case of producer gas, which was always nearly at atmospheric pressure, the density might be taken as nearly constant. A question had been asked as to how he made sure there were no eddies. His answer was, that he did not make sure. There was an experiment described in Appendix IV (page 287) dealing with that part of the subject, in which he stated that he put in a stream of smoky air into his main air-stream, in order to show what eddies there were.

In conclusion, he wished to be allowed to thank those gentlemen who had taken part in the discussion.

Communication.

Mr. C. H. Wingfield wrote that the author attributed the "suction" in a piece of tube placed across the path of a column of air to motion imparted to its contents (page 250). The writer thought the explanation he had himself given * in the Proceedings of the Institution of Civil Engineers (1901–2, vol. cxlvii, page 234) a more probable one, as it accounted better for the action of Professor Unwin's discs, Fig. 13 (page 302), and also for the fact that such "suction" did not occur when the side-tube ended flush with the

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* This was the effect that, when air blows across the cylindrical part of a projecting tube, the pressure on the leeward side of the latter is less than elsewhere. Air tends to flow into this space of low pressure from all points, and the air which thus tends to come from the tube reduces the pressure in the latter below the true pressure of the air in the main current. Professor Unwin's discs shield the end of the tube from this low-pressure space. When the tube does not project, the air cannot blow across the cylindrical part, and cannot therefore form a space of low pressure behind it.

(Mr. C. H. Wingfield.)

interior of the air-duct. He did not know whether the author would consider it a "proper" theory (page 250, line 13), but it certainly fitted the facts.

He was rather surprised to see no mention of the side-gauge tip which was used by the Pennsylvania Railway, and which he had described in the place cited above, as, though Professor Unwin's discs were excellent if the flow of air was normal to the axis of the tube, he did not think they were free from error when this was not the case. Since, as pointed out by the author on page 248, this motion of the air was turbulent, and therefore not always parallel to the face of the disc, it would seem that the wire-gauze sandwich used by the Pennsylvania Railway Company would be likely to give more exact results. It had been proved to be quite unaffected by the direction in which air-currents struck it.

The experiments described in the Paper seemed to confirm very satisfactorily the general belief of engineers as to the accuracy of the Pitot-tube method of measuring velocities.

Mr. Threlfall wrote, in reply to Mr. Wingfield, that it was a fact that flanged gauges did in general give a slight suction as stated by him. The wire-gauze side-gauge referred to was not known to the author when working with air of measured velocity, or he would have examined it. Some trials were, however, made with a side-gauge plugged with cotton-wool—a practice which had been in use for years, and which gave quite good results; such side-gauges were unsuitable for producer-gas, because they got clogged by tar.

In regard to the action of simple apertures opening into the sides of the air-duct, the author could confirm Mr. Wingfield's statement that they gave no suction; but he had always regarded the explanation of this as depending on the absence of motion at the boundary. Mr. Wingfield's theory of side-gauge suction was interesting, but was certainly not a "proper" theory in the author's use of the term, which was meant to imply a complete hydrodynamical theory without "simplifications," and giving quantitative results.

The Institution of Mechanical Engineers.

PROCEEDINGS.

March 1904.

An Ordinary General Meeting was held at the Institution on Friday, 18th March 1904, at Eight o'clock p.m.; J. Hartley Wicksteed, Esq., President, in the chair.

Before proceeding to business, the President asked the Members to rise with him in order that they might, by a silent vote, express their condolence at the loss of a soldier of the Royal House—the Duke of Cambridge—who had been an Honorary Member for more than twelve years, and who had twice honoured the Institution by his presence at its Anniversary Dinners—in 1892 and 1897. On both these occasions all those who had been present would remember the straightforward, manly, common-sense speeches which he made. The late Duke of Cambridge had departed leaving nothing but regrets; and he thought that few men ever lived for eighty-five years without making a single enemy so completely as he had done. The Members felt the loss not only to themselves, but they also sympathised with the late Duke's family, with the King, and with his royal connections. His Royal Highness was, he thought, the last of his generation, and was distinguished by the great qualities characteristic of his race.

The vote was carried in silence, all the Members upstanding.

The Minutes of the previous Meeting were read and confirmed.

The President announced that the Ballot Lists for the election of New Members had been opened by a committee of the Council, and that the following eighty-two candidates were found to be duly elected:—

MEMBERS.

Ames, Richard,	Nottingham.
Eager, John,	Burry Port.
Haden, William Nelson,	Trowbridge.
Hookham, John Albert,	Stoke-on-Trent.
Howlden, Edwin Francis,	Doncaster.
Knowles, John William,	Bradford.
Miller, David,	Liverpool.
Motion, Robert,	Glasgow.
Norman, James,	London.
Pattinson, Joseph,	Newport, Mon.
Thomson, George,	Edinburgh.
Warlow, Frederick Arthur,	Sheffield.
White, Charles Fitzwilliam,	Lahore.
Wood, Walter James,	Great Grimsby.
Woolliscroft, George William,	Derby.

ASSOCIATE MEMBERS.

Back, Walter Herbert,	Great Yarmouth.
Bell, Allan,	Liverpool.
Bent, John Bradbury,	Leicester.
Berry, Robert,	Manchester.
Bharucha, Fakirjee Edulje,	Lahore.
Bland, John William,	Bradford.
Burt, John William Edward,	Cardiff.
Cox, Kenneth Robert William,	Manchester.
Croft, Frank,	Bradford.
Dobson, Benjamin Palin,	Bolton.
Don, John,	Peterhead.
Evans, Malcolm Thomas,	Manchester.
Forsyth, Reginald James,	Manchester.
Forsyth, William,	Chichigalpa, Nicaragua.

Fradley, Herbert Thomas	Dublin.
Gavey, Arthur	Johannesburg.
Gill, Charles Edgar	New Orleans.
Girling, Herbert Charles	Newcastle-on-Tyne.
Goodacre, William Geoffrey	Derby.
Hesketh, Thomas	Folkestone.
Hussey, Frederick Kinneer Eyre	London.
Kitchin, William Archibald	London.
Lake, Henry Barker	Birmingham.
Langdon, Harold Arthur William	Tucacas, Venezuela.
Leber, John Henry	London.
Lewis, William Yorath	Grays, Essex.
Lishman, John James	Las Palmas.
Mackenzie, Alfred Douglas	London.
Mackessack, Harry	Newcastle-on-Tyne.
Mansfield, Frank	Sydney.
Matthews, William Edward	Cardigan.
Maw, Robert Lewis	London.
McClure, John Raynes	Los Angeles, Cal.
McDermott, Hugh	London.
Murdoch, Alexander Gemmell	London.
Nelson-Barrett, John Mathew	Delhi.
Rhodes, Charles Joseph	Wakefield.
Sandaljian, Bedros	London.
Smith, Cades Alfred Middleton	London.
Smyth, Robert Henry	Uitenhage.
Stonebridge, Arthur Watson	London.
Sweatman, Harry	London.
Symons, James Francis	London.
Thom, John	London.
Wadham, Robert	Stockholm.
Ward, Augustine Melliar	Dartford.
Williams, Daniel	Manchester.
Wilson, William Euston	Penang.

GRADUATES.

Atkins, Arthur Henry,	London.
Brockley, Carl Wilton,	Stroud, Glos.
Bussey, Lionel Ernest,	London.
Carter, Ernest,	Jalpaigure, India.
Child, Percy Douglas,	Ipswich.
Cryer, James Wilfred,	Bolton.
Denman, John Percy,	London.
Engert, Fredrick Percy,	London.
Engholm, Frank Goldie,	London.
Everington, Charles Gordon,	Erith, Kent.
Harris, John Edward,	Chester.
Hodgson-Stevens, Antonio Rodovalho,	London.
Hughes, William Clare,	London.
Law, Horace Cecil,	Birmingham.
Lloyd, George Wilmot,	London.
MacCallum, Andrew Humphrey,	London.
Nash, Henry Algernon Fraser,	London.
Perrott, William,	Cork.
Richardson, John Stocks,	Leeds.

The President announced that the following fifteen Transferences had been made by the Council since the last Meeting:—

Associate Members to Members.

Atkinson, Frederic,	London.
Atkinson, Henry,	London.
Barrow, Louis,	Birmingham.
Barty, Alexander Douglas,	Prescot.
Fox, Henry Shoolbred,	London.
Gilling, Arthur Hewitt,	Liverpool.
Graham, Hubert Berger,	Birmingham.
Hunt, Henry,	London.
Johnston, Charles Morison,	Shrewsbury.

MACIVOR, ALEXANDER,	Durban.
STEPHENS, CHARLES ROBERT,	Falmouth.
WALLER, WILLIAM,	London.
WILKINSON, FRANCIS ALAN,	London.
WYLD, WILLIAM,	Doncaster.

Graduate to Associate Member.

MARTENS, HUBERT BINGON,	London.

The following Paper was read and partly discussed:—

"Compound Locomotives in France"; by M. EDOUARD SAUVAGE, *Member*, Chief Consulting Engineer, Western Railway of France.

The Meeting terminated at Ten o'clock. The attendance was 189 Members and 114 Visitors.

The Institution of Mechanical Engineers.

PROCEEDINGS.

April 1904.

An Ordinary General Meeting was held at the Institution on Friday, 15th April 1904, at Eight o'clock p.m.; J. Hartley Wicksteed, Esq., President, in the chair.

The Minutes of the previous Meeting were read and confirmed.

The President announced that the Ballot Lists for the election of New Members had been opened by a committee of the Council, and that the following eighty candidates were found to be duly elected:—

MEMBERS.

Baxter, George Handyside,	Glasgow.
Buckley, Edwin William,	Manchester.
Clark, Henry,	Sunderland.
Cochrane, Thomas Henry, Captain R.E.,	Rochester.
Eastwood, William,	Preston.
Haney, Hubert Decimus,	Buenos Aires.
Keay, James,	Birmingham.
Lawes, George Elliot,	Monte Caseros.
Little, John,	Sheffield.
McMahon, Peter Valentine,	London.
Miles, William Edward,	Woolwich.
Partridge, Henry Ralph Champion,	Bolton.
Rought, Charles,	London.
Spurrier, Henry,	Preston.
Watt, Adam,	Hartlepool.

ASSOCIATE MEMBERS.

Barclay, Wallace,	Glasgow.
Barnes, Archibald,	Sheffield.
Blaker, Alexander Aubrey,	London.
Cawthra, James Herbert,	South Shields.
Coulton, Ivor Bertie,	Dublin.
Daniel, William Henry,	Leeds.
Douglas, Charles Edward,	Manchester.
Dow, Harold Percy,	London.
Edward, Frank,	Stroud, Glos.
Ellis, Jesse, Jun.,	Maidstone.
Farnham, William Augustus,	Sidcup, Kent.
Goodbehere, Eric,	Basle.
Gregson, Bryan Padgett,	London.
Griffiths, Ralph Stanley,	London.
Guyatt, David John,	Wednesbury.
Hall, Samuel,	Plymouth.
Hanbury, Herbert Wood,	Glasgow.
Harden, George Frederick St. Clair,	Glasgow.
Hart, Herbert Alfred,	Cardiff.
Kenyon, George Cecil,	Liverpool.
Kitchen, Jonathan,	Luton.
Luke, Richard Montague,	Plymouth.
Manuel, Constantine,	London.
Marshall, Reginald,	London.
Martin, Percy,	Coventry.
Michell, William Henry, Engineer-Lieut., R.N.,	Portsmouth.
Newton, Percy,	Wolverhampton.
Parkin, Thomas,	Sheffield.
Pownall, Joseph Harold,	Grimsby.
Purse, Frederick Walter,	Warrington.
Reeve, Robert John Robey,	London.
Rigby, Thomas,	Manchester.
Robey, Ernest William,	London.
Rogers, Ernest Henry,	Manchester.
Rossiter, William Morgan,	London.

Schofield, Samuel Dean,	Shipley, Yorks.
Soames, Ernest Arthur,	London.
Seling, Arthur Lawrence,	Hull.
Strong, William Henry,	Bristol.
Sutcliffe, Ingham,	Lincoln.
Walker, Arthur,	London.
Wells, Edward Nelson,	London.
White, Thomas Hyler,	West Croydon.
Whitehouse, George Henry,	Tipton.
Williams, Charles,	Bristol.
Willis, George Oswald Bell,	Bolton.
Willshear, Edward,	London.
Wiswall, John William,	Runcorn.

GRADUATES.

Briggs, Richard John Percival,	London.
Colley, Robert William,	Bedford.
Ellington, Noel Bayzand,	Winterthur.
Gordon, William Robert,	Glasgow.
Hodgson, Harold Cecil,	London.
Lloyd, William Edward,	Guildford.
Malthouse, James William,	Birmingham.
Marshall, Albert Edward,	London.
Northcott, Henry Hans Macfarlane,	London.
Owen, Halsall,	Warrington.
Roberts, Robert James,	London.
Smith, Harold,	Manchester.
Smith, Stanley Carlton,	Bedford.
Smith, William Garner,	London.
Stringer, Robert,	Preston.
Toby, Arthur Ivon,	Paignton.
Watson, Herbert Sanderson,	Sunderland.

The President announced that the following five Transferences had been made by the Council since the last Meeting:—

Associate Members to Members.

Dronsfield, James	Oldham.
Epton, William Martin,	Johannesburg.
Newell, Ernest,	Gainsborough.
Petter, Ernest Willoughby,	Yeovil.
Ryder, George Albert,	Bolton.

The Discussion was resumed and concluded on the following Paper:—

"Compound Locomotives in France"; by M. Edouard Sauvage, *Member*, Chief Consulting Engineer, Western Railway of France.

The Meeting terminated at Ten o'clock. The attendance was 132 Members and 62 Visitors.

ANNIVERSARY DINNER.

The Anniversary Dinner of the Institution was held at the Hotel Cecil, Strand, London, on Thursday evening, 14th April 1904. The President occupied the chair; and the following were among the Guests who accepted the invitations sent to them, although those to whom an asterisk * is prefixed were unavoidably prevented at the last from being present.

The Right Hon. Sir Edward Fry, D.C.L., LL.D., F.R.S., President of the Court of Arbitration, Metropolis Water Act 1902; The Right Hon. Henry Hobhouse, M.P.; Sir John Wolfe Barry, K.C.B., LL.D., F.R.S., Member of the Court of Arbitration, Metropolis Water Act 1902; Sir George C. T. Bartley, K.C.B., M.P.; Sir John Hollams; Lt.-Colonel H. C. L. Holden, F.R.S., Superintendent, Royal Gun Factory, Woolwich; Captain C. H. Stockton, Naval Attaché, United States Embassy; *Mr. F. T. Marzials, C.B., Accountant-General of the Army; *Mr. E. M. Beachcroft, Chairman of the Metropolitan Water Board; The Hon. J. D. FitzGerald, K.C.; Dr. William Garnett, Secretary of the Technical Education Board, London County Council; Mr. J. H. Balfour Browne, K.C.; *Mr. C. A. Cripps, K.C., M.P.; *Mr. C. W. Darley, Consulting Engineer to the New South Wales Government.

Sir William H. White, K.C.B., LL.D., F.R.S., President of the Institution of Civil Engineers; *Sir Norman Lockyer, K.C.B., LL.D., F.R.S., President of the British Association; Dr. R. T. Glazebrook, F.R.S., President of the Physical Society; Mr. R. K. Gray, President of the Institution of Electrical Engineers; Mr. Albert Buck, President of the Surveyors' Institution; Mr. Alfred Saxon, President of the Manchester Association of Engineers; Mr. D. B. Butler, President of the Society of Engineers; Mr. H. E. Jones, President of the Institution of Gas Engineers.

*Mr. Dugald Clerk; Mr. Richard Dalgliesh; Mr. R. A. McLean, Auditor; *Mr. H. L. Millar, Treasurer; Mr. Arthur Paget, Secretary to the Court of Arbitration, Metropolis Water Act 1902; Dr. T. E. Stanton; Captain A. G. Stevenson, R.E., Central South African Railways; Mr. C. E. Stromeyer; *Mr. Richard Threlfall, F.R.S.

The President was supported by the following officers of the Institution.—*Past Presidents*, Sir Edward H. Carbutt, Bart.; Mr. Samuel W. Johnson; Dr. Alexander B. W. Kennedy, F.R.S.; *Mr. William H. Maw; Mr. E. Windsor Richards; and *Mr. Percy G. B. Westmacott. *Vice-Presidents*, Mr. John A. F. Aspinall; Mr. Edward B. Ellington; *Mr. Arthur Keen; Mr. Edward P.

Martin, and Mr. A. Tannett-Walker. *Members of Council.*—*Mr. Henry Davey; Mr. Henry Lea; *Sir William T. Lewis, Bart.; Mr. Michael Longridge; Mr. James Mansergh, F.R.S.; Mr. Henry D. Marshall; and Mr. J. F. Robinson.

After the President had proposed the loyal toasts, Captain C. H. STOCKTON, United States Naval Attaché, proposed that of the "Houses of Parliament," which was acknowledged by Sir GEORGE C. T. BARTLEY, K.C.B., M.P.

In proposing the toast of "Scientific Education," Dr. ALEX. B. W. KENNEDY, F.R.S., Past-President, referred to the progress which the scientific training of engineers had made during the past thirty years. In 1874 there was hardly a single complete engineering course of any kind in London; now, no important town felt that its educational system was complete unless it included a full engineering course. He was not sure that we were free from the danger of going wrong in the manner, rather than in the matter of scientific education, so far as their profession was concerned. They would never get the scientific side of engineering properly dealt with unless their teachers could be persuaded that science, to Engineers, was not an end in itself, but a means to an end.

The Right Hon. HENRY HOBHOUSE, M.P., responding to the toast, said that one must be blind, indeed, not to recognise in the circumstances of the present day that there was a growing need for more training and instruction in science than there was in the past. But in our zeal for science it must not be forgotten that all scientific education, to be of any avail, must be founded on a firm basis of sound general education.

Mr. J. H. BALFOUR BROWNE, K.C., in proposing the toast of "Kindred Societies," referred to the danger of carrying specialism in the engineering profession too far, and suggested that the profession was separated and segregated into different camps by mere names.

Sir **William H. White**, K.C.B., President of the Institution of Civil Engineers, in reply, said it had been suggested that the engineering societies of this country were not so united as they might be. As a matter of fact, the Institution of Civil Engineers had, from the moment of its establishment, contemplated and embodied the idea of unity among the different branches of the profession. There was no branch of engineering, except the military, which did not find its home in that Institution, and that was the reason why, on occasions like this, the President of the Institution of Civil Engineers stood forward to represent the Kindred Societies. The different societies had not their lines of demarcation firmly determined. There was nothing of the kind such as existed amongst trade unionists, where one man could put in a pipe measuring 2¼ inches in diameter, while a man of a different class had to be found to put in one which measured 3 inches. Engineers looked upon Mechanical Engineering as affording, in some sense, a common meeting ground—the foundation—of much of their work. They all recognised that the members of the profession who devoted themselves to mechanical engineering helped those of the kindred societies in a wonderful and never-failing way.

Dr. R. T. **Glazebrook**, President of the Physical Society, also responded to the toast.

Sir **Edward H. Carbutt**, Bart., Past-President, proposed the toast of "Our Guests," which was acknowledged by Sir **John Hollams** and Lieut.-Colonel H. C. L. **Holden**, F.R.S.

The Right Hon. Sir **Edward Fry**, in proposing the toast of "The Institution of Mechanical Engineers," mentioned that the Institution was founded in 1847, and described its gradual progress from small beginnings to its present important position, there being now upwards of 4,100 members. He also expressed the great obligations felt to the Institution by the Arbitrators under the Metropolis Water Act, 1902, for the hospitality which they had received in the House of the Institution.

The President briefly responded to the toast, and expressed his appreciation of the possibilities which, as indicated by Sir Edward Fry, modern discoveries promised to open up to the mechanical engineer.

COMPOUND LOCOMOTIVES IN FRANCE.

By M. EDOUARD SAUVAGE, *Member*,

Chief Consulting Engineer, Western Railway of France.

A Paper on "Recent Locomotive Practice in France,"[*] read before the Institution four years ago by the author of the present Paper, had the honour of an elaborate discussion. At the conclusion the author was informed that further details on the subject would be acceptable, and this is an excuse for the present new communication on the same subject.

For a complete appreciation of a class of locomotives, as of any machine used for industrial purposes, it is necessary to know first of what service it is capable, that is to say, what weight of train the locomotive is able to haul with a given speed on a given line; secondly, the expenses, by which this service is bought, must be considered. As pointed out by Mr. John A. F. Aspinall,[†] economy in locomotive working does not mean only economy on the coal bill, but on the total expenses of locomotive service; and this question cannot be considered as definitely settled until the superiority of a certain class of engines, say of compound locomotives, is demonstrated by unimpeachable figures. As regards marine engines, very few people indeed, if any, doubt that the multiple expansion engine must be preferred to the simple one; but opinions are far from uniform when locomotives are considered.

Really scientific data on the working of locomotives are very scarce. It seems that the best plan for collecting such data is to test the locomotive in a specially equipped laboratory, as at the Purdue University in the United States of America, and in the Swindon

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[*] Proceedings June, 1900, page [illegible]

[†] *Ibid* [illegible], page [illegible].

Works of the Great Western Railway. In such tests, coal and water consumption, indicated and effective power, can be measured under perfectly defined conditions, which may be altered one by one in experiments of sufficient duration. It is to be regretted that such tests have been so seldom made; it must however be observed that, although they would furnish very useful data for practice, still they could not give in every case the best practical solution, for which the numerous ever-changing conditions of service must be taken into account.

As regards compound locomotives in France, all available data are results of experimental runs on one hand, and of a prolonged service on the other.

The interest of French locomotive practice exists in the development of the four-cylinder compound, which permits a marked increase in the weight and speed of the trains. The main French railways continue to build or to order locomotives of this class.

Whilst Table 1 in the Proceedings 1900 (pages 398 and 399), mentioned 803 such locomotives in use or on order on the 1st January 1900, for ordinary gauge railways alone, this number had been increased to 1577 by the 1st October 1903 (narrow-gauge locomotives excluded). To these must be added (always considering exclusively the stock for ordinary gauge) a few two-cylinder and three-cylinder compounds.

Table 1 (pages 329–331) gives the statistics of the four-cylinder compounds on the 1st October 1903.

The majority of these engines belong to two classes, which may be considered as standards in France, the express locomotive, with four large coupled-wheels, of 2 mètres (6 feet $6\frac{3}{4}$ inches) diameter or a little more, and the six-coupled locomotive, with diameters of 1·600 m. to 1·750 m. (5 feet $2\frac{15}{16}$ inches to 5 feet $8\frac{7}{8}$ inches),* both

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* The abbreviations for the metric units have been given at length in the Proceedings (1900, page 393). In this Paper the following will be used:— *m* for mètre, *mm* for millimètre, m^2 for square mètre, cm^2 for square centimètre, *g* for gramme, *kg* for kilogramme, *t* for tonne (1000 kg), *l* for litre. Weights are given in metric tons of 1000 kg; the English ton is equal to about 1016 kg, exactly to 1016·018 kg, by Act of Parliament of 1864.

TABLE 1 (*continued on next page*).

Four-cylinder Compound Locomotives, in use or on order on 1st October [illegible].

(Ordinary French gauge.)

LOCOMOTIVES WITH TWO DRIVING AXLES.

Fig.	Railway.	Nos. of the Series.	No.	Total.	Year ordered.	Remarks.
1	Nord (Northern)	701	1		1885	Driving axles not coupled; radial axle in front
		2121-2137	17		1890 and 1892	
		2138-2157	20		1894	
		[illegible]	[illegible]		1895 and 1897	
		2641-2642	2		1899	Type "Atlantic."
		2643-2660	18		1901	Do.
		2661-2675	15	[illegible]	1902	Do.
	Ouest (Western)	501-502	2		1894	
		503-542	40		1897 and 1899	
		543-562	20	62	1900	
	Etat (State)	2701-2706	6		1899	American locomotives. Vauclain system.
		2801-2804	4	10	1900	
	Paris-Orléans	1-25	25		1898 and 1899	
		3001-3008	8	33	1902	Type "Atlantic."
	Midi (Southern)	1701-1714	14		1892 and 1893	
		1751-1774	24		1895	
		1775-1784	10		1898	
		1901-1910	10	58	1901	Type "Atlantic."
	P. L. M. (Paris, Lyons and Mediterranean)	C 1-2	2		1892	Two driving axles (coupled) between carrying axles
		C 3	1		1892	
		C 11-12	2		1894	
		C 21-60	40		1895	
		C 61-150	90		1898	
		C 151-180	30	165	1900	
8	Est (Eastern)	[illegible]	[illegible]		[illegible]	
		[illegible]	2	[illegible]	[illegible]	Type "Atlantic."
	Total No. of Locomotives with 2 driving axles	—		[illegible]		

TABLE 1 (*continued on opposite page*).

Four-cylinder Compound Locomotives, in use or on order on 1st October 1903.

(Ordinary French gauge.)

LOCOMOTIVES WITH THREE DRIVING AXLES.

Fig.	Railway.	Nos. of the Series.	No.	Total	Year ordered.	Remarks.
	Nord (Northern)	3121–3170	50		1897	
		3171–3225	55	105	1901	
	Ouest (Western)	2501–2525	25		1898	
		2526–2540	15		1900	
2		2701–2720	20	60	1900 and 1903	
	Etat (State)	3701–3730	30	30	1900	
	Paris-Orléans	1701–1725	25		1899	
		4001–4015	15	40	1902	
	Midi (Southern)	1301–1302	2		1895	
		1303–1312	10		1897	
		1401	1		1895	
		1402–1415	14		1897	
		1313–1350	38		1900 and 1901	
		1416–1425	10	75	1901	
	P. L. M. (Paris, Lyons, and Mediterranean)	3261–3300	40		1897	Locomotives with four driving-axles converted.
		3401–3650	250	290	1898 to 1901	
	Est (Eastern)	3401–3460	60		1898	
		3461–3500	40		1900	
3 8 9		3501–3520	20		1900	
		3521–3550	30		1900	
10		3101–3102	2		1901	
		3551–3580	30		1901	
		3581–3610	30	212	1903	
4	Ceinture	51–65	15	15	1902	Tandem compound.
	Total No. of Locomotives with 3 driving axles	. . . . .		827		

(*continued from page 327*) TABLE 3.

Four-cylinder Compound Locomotives, in use or on order on 1st October 1903.

(Ordinary French gauge.)

LOCOMOTIVES WITH FOUR DRIVING AXLES.

Fig.	Railway.	Nos. of the Series.	No.	Total.	Year ordered.	Remarks.
	Nord (Northern)	4101–4120	20	20	1903	Woolf's system, 4 tandem cylinders.
	Paris-Orléans	2001–2013	13	13	1903	
	Midi (Southern)	4001–4002 4003–4017	2 15	17	1896 1901	
	P. L. M. (Paris, Lyons, and Mediterranean)	[illegible] [illegible] [illegible] [illegible]	3 1 113 129	246	1889 1892 1892 and 1893 1894 to 1902	Converted engines.
10, 11	Est (Eastern)	[illegible]	2	2	1903	
	Total No. of Locomotives with 4 driving axles			298		

Total No. of Four-cylinder Locomotives 1???

(This does not include Mallet locomotives for the narrow-gauge light railways.)

being fitted with a bogie in front. The six-coupled locomotives are equally fit for goods and for ordinary passenger trains. A tendency must be noticed to increase the diameter of the six-coupled wheels of these engines to about 2 m. (6 feet $6\frac{3}{4}$ inches), for enabling them to work express trains: for instance, this has recently been done on the Eastern, Paris-Orléans, and Western Railways. On the other hand, the "Atlantic" type is resorted to for increasing the power of express locomotives, the boiler and particularly the fire-box being enlarged.

In some cases, specially for working goods trains on heavy gradients, eight-coupled locomotives are used, with no other wheels on the P.L.M. system, and with a pony truck in front on the new engines of the Southern, Eastern, and Paris-Orléans Railways.

In addition to these four-cylinder locomotives, the Southern Railway has rebuilt some engines as two-cylinder compounds, with six-coupled wheels and a pony truck in front. The same company is now rebuilding old express locomotives as two-cylinder compounds.

Mention must be made also of a four-cylinder tandem compound tank-engine (described below), built by the Northern Railway for working trains on the Ceinture line of Paris.

The principal dimensions of many of the four-cylinder compounds have been given already in Table 2 (Proceedings 1900, pages 400–407); the dimensions of new types and of older types when alterations took place will be found in the following descriptions.

I. *Four-Cylinder Compound Locomotives with two-coupled Axles.*

The Northern Railway has added to its stock 33 "Atlantic" locomotives (Nos. 2643–2675), similar to the two ordered in 1898 (Nos. 2641–2642), of which one was conspicuous in the Paris Exhibition of 1900, Fig. 1, Plate 50; slight alterations have been made to the previous type: the distance of the bogie wheels has been increased from 1·800 m. to 2·000 m. (5 feet $10\frac{7}{8}$ inches to 6 feet $6\frac{3}{4}$ inches), to obtain a greater stability; the length of tubes, which was 4·200 m. (13 feet $9\frac{3}{8}$ inches) between plates, is 4·300 m. (14 feet $1\frac{5}{16}$ inches) in the new engines. The fittings of the cab have been altered, the driver being transferred to the left side. It being desirable to preserve the same distance between the extreme wheels of the locomotive with its tender, in order to use the existing 17 m (55 feet 9 inches) turn-tables, the old plan of supporting the tender on three axles instead of two bogies has been reverted to; at the same time this plan gave more room for a water scoop.

The Southern Railway has recently ordered ten (Nos. 1901–1910), and the Eastern Railway two (Nos. 2601–2602) "Atlantic" locomotives (Fig. 8, Plate 52) similar to those on the Northern Railway.

The new "Atlantic" (Nos. 3001–3008), recently built for the Paris-Orleans Railway by the Société Alsacienne de Constructions Mécaniques, Fig. 5, Plate 51, is of special interest as being the most powerful express locomotive as yet made for the French lines. The principal dimensions are as follows on Table 2:—

TABLE 2.

Principal dimensions of "Atlantic" locomotives of the Paris-Orléans Railway.

Boiler:	
Internal diameter	1·418 m (4 ft. 7⅞ ins.)
Height of axis above rail	2·700 m (8 ft. 10¼ ins.)
Working pressure	16 kg per cm² (228 lbs. per sq. in.)
Tubes:	
Length between plates	4·400 m (14 ft. 5¼ ins.)
External diameter	70 mm (2¾ ins.)
Number (ribbed tubes)	[illegible]
Grate area	2·4 m² ([illegible] sq. ft.)
Heating surface	[illegible] m² ([illegible] sq. ft.)
Cylinders:	
H.P. diameter	360 mm (14[illegible] ins.)
Stroke	640 mm (25¼ ins.)
Cylinders:	
L.P. diameter	600 mm (23⅝ ins.)
Stroke	640 mm (25¼ ins.)
Driving wheels, diameter	2·040 m (6 ft. 8[illegible] ins.)
Weight:	
Total in working order	[illegible] kg ([illegible] tons)

The adhesive weight is 36 *t* (18 *t* per axle), and it is expected that this weight will be increased to 40 *t*. Such a change is easy in locomotives of this type.

The "Atlantic" locomotives have been found far superior to the older express compounds. On the Northern Railway, during the Exhibition of 1900, the "Nord-express" trains were worked either by the old compounds (Nos. 2158–2180), or by the new "Atlantic" 2641, between Paris and Jeumont. The distances and schedule of the trains are as follows on Table 3 :*

TABLE 3.

Schedule of "Nord-Express" train.

		Time.	Distances.		Average Speeds.	
		p.m.	Kilomètres. *Miles.*		Kilomètres per hour. *Miles per hour.*	
Paris . . .	dep.	1.50	—		—	
Creil . . .	pass	2.24	50·3 31·26	153·1 95·14	83·7 52·00	90·0 55·92
Compiègne . .	pass	2.44	33·3 20·69		100·0 62·13	
Tergnier . .	pass	3.15	47·3 29·39		91·5 56·85	
St. Quentin { .	arr. dep.	3.32 3.36	22·2 13·79		78·5 48·77	
Jeumont . .	arr.	4.34		84·8 52·69		87·0 54·05

The regular composition of the trains was seven bogie carriages and two vans, weighing altogether 270 *t.* (265·73 tons). With the locomotives Nos. 2158 to 2180, that weight was never exceeded, and, if necessary, a second train was run. On the contrary, there was no limit with the "Atlantic" locomotive 2641, and the run was always made in less than the booked time.

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* A new schedule has been made with a saving of three minutes between Paris and St. Quentin, and one minute between St. Quentin and Jeumont.

Table 4 (pages 336–337) gives details of some runs between Paris and St. Quentin.

Fig. 13, Plate 55, gives the profile of the line from Paris to Charleroi.

The following remarks may be made: the acceleration was rapid although the train was heavy*; as a rule the train passed St. Denis, at a distance of 6 km (3·7 miles), regularly 6 minutes after starting. The time from St. Denis to Survilliers, 23·5 km. (14·6 miles), mostly on a rising gradient of 1 in 200, varied from 14 minutes 30 seconds (average speed 97 km an hour (60·2 miles per hour)) to 16 minutes 50 seconds (84 km an hour (52·1 miles per hour)). The speed was 90 km (55·9 miles) with the heaviest train. Down grades the speed was generally 120 km an hour (74·5 miles per hour), and might have been exceeded without difficulty.

The level part from Creil to Tergnier, 80·6 km (50 miles), took as an average 48·5 minutes: mean speed, 100 km an hour (62·1 miles per hour), which might easily have been exceeded. The actual speed on that section varied from 105 to 110 km (65·2 miles to 68·3 miles), to make up for the time lost in slowing up at Creil, at Compiègne (slightly), and at Tergnier (slightly, speed 80 km (49·7 miles)).

The Northern Railway officers are of opinion that a train weighing 300 *t* (295·2 tons) may be taken from Paris to St. Quentin in 1 hour 32 minutes, at an average speed of 100 km. an hour (62·1 miles an hour).

With a train weighing 200 *t* (196·8 tons), an average speed of 105 km. an hour (65·2 miles an hour) has been maintained between Paris and Amiens, namely, 100 km (62·1 miles) from Paris to Creil, and 109·5 km. (68 miles) from Creil to Amiens. It

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* Proceedings, June 1900, page 425, Mr. J. D. Twinberrow: "*Le démarrage doit être rapide.*"

TABLE 4 (*continued on opposite page*).

Details on some runs from Paris to St. Quentin of the "Nord Express" Train, hauled by Compound "Atlantic" Locomotive No. 2641.

Distances.		Stations.	26 June, 1900.	13 July, 1900.	17 July, 1900.	29 Aug. 1900.
From Paris.	Between stations.					Weights
Km. *Miles.*	Km. *Miles.*		Tonnes 335 *Tons* 329·7	300 295·2	290 285·4	339 333·6
			h. m. s.	h. m. s.	h. m. s.	h. m. s.
—	— 6·1 3·7	Paris . dep.	1 50 0	1 56 0 (6 m. late)	1 50 0	1 50 0
6·1 3·7	23·6 14·6	St. Denis pass	1 56 11	2 2 0	1 55 30	1 56 20
29·7 18·4	20·6 12·8	Survilliers pass	2 13 0	2 17 0	2 10 0	2 13 0
50·3 31·2	33·3 20·6	Creil . pass	2 24 0	2 28 0	(*b*)2 22 0 (2 m. before time)	2 24 15
83·6 51·9	47·3 29·3	Compiègne pass	2 44 0	2 48 0	2 43 0 (1 m. before time)	2 45 15
130·9 81·3	22·2 13·7	Tergnier pass	(*a*) 3 12 0 (3 m. before time)	3 15 0 (booked time)	3 11 0 (4 m. before time)	3 15 0 (booked time)
153·1 95·2		St. Quentin arr.	3 29 0 (3 m. before time)	3 30 0 (2 m. before time)	3 27 0 (5 m. before time)	3 31 0 (1 m. before time)
Time from Paris to St. Quentin			1 39 0	1 34 0	1 37 0	1 41 0
Average speed . . .			Km. 92·7 *Miles* 57·6	97·7 60·7	94·7 58·8	91·0 56·5

(*concluded from opposite page*) TABLE 4.

Details on some runs from Paris to St. Quentin of the "Nord Express" Train, hauled by Compound "Atlantic" Locomotive No. 2641.

15 Sept 1900	23 Sept 1900	27 Sept 1900	8 Oct 1900	13 Oct 1900	Remarks
of Trains					
311 [illegible]	325 [illegible]	325 [illegible]	311 [illegible]	365 [illegible]	
h. m. s. 1 50 0	h. m. s. 1 50 0	h. m. s. 1 50 0	h. m. s. 1 55 0 (5 m. late)	h. m. s. 1 51 30	(a) Slowing up by signal at Tergnier.
1 56 30	1 56 0	1 56 0	2 1 0	1 57 45	
2 13 0	2 12 0	2 11 0	2 17 0	2 13 30	(b) Slowing up by signal at Creil.
2 24 0	2 23 0 (1 m. before time)	(c)2 23 0 2 25 0	2 28 0	2 24 0	
2 44 0	2 43 0 (1 m. before time)	2 48 0	2 48 0	2 44 15	(c) Stop by signal.
3 13 0 (2 m. before time)	3 13 0 (2 m. before time)	3 14 30	3 14 30	(d)3 11 30 (3½ m. before time)	(d) Passed post 100 at 2 hrs. 54 ms.
3 29 0 (3 m. before time)	3 28 0 (4 m. before time)	3 29 0 (3 m. before time)	3 30 0 (2 m. before time)	3 28 30 3½ m. before time	
1 39 0	1 38 0	1 39 0	1 35 0	1 37 0	
92·7 57·6	93·7 58·2	92·7 57·6	96·7 60·0	94·7 58·8	

is worthy of remark that the speed on the rising gradients (1 in 200) was equal to the average.

With trains of 300 to 350 *t* (295·6 to 344·4 tons), the coal consumed was 12·5 kg per km (44·36 lbs. per mile), of which 300 kg (661·1 lbs. or 6 cwt.) was on the grate before starting. The service of the new "Atlantics" and of the sister engine No. 2642 is equally good.

For instance, from Calais to Paris the trains wait for the arrival of the Dover boat. In case of delay of the boat the time lost has been frequently made up by the train. As much as 21 minutes have been saved, as follows on Table 5:—

TABLE 5.

Train No. 12 *bis, 5th March* 1902; *Locomotive No.* 2642; *Weight,* 245 *t* (241 *tons.*)

Distances from Paris.	Stations.		Booked times.	Actual times.
Km. *Miles.*			P.M.	P.M.
297·2 184·6	*Calais-Maritime .	dep.	1.15	1.40
175·4 108·9	Abbeville . .	arr. dep.	2.39 2.44	2.59 3.04
130·6 81·1	Amiens . . . (slowing up)	pass.	3.13	3.31
50·3 31·2	Creil . . .	pass.	4.09	4.18
	Paris . . .	arr.	4.45	4.49
	Average running speed . . .		86·9 km. 53·9 *miles.*	96·9 km. 60·2 *miles.*

* 25 minutes late, waiting for boat.

Fig. 14, Plate 56, gives the profile of the Paris-Calais line.

A special train (*train de luxe*) is run on Tuesdays, Wednesdays, Fridays, and Sundays as follows, with a booked average speed of 93·3 km an hour (57·9 miles per hour), after the following schedule:—

TABLE 6.

Schedule of Train 67.

Distances from Paris	Stations.		Time.
Km. Miles.			
—	Paris-Nord .	dep.	A.M. 11.40
50·6 31·4	Creil	pass	P.M. 12.21
126·0 78·3	Longueau . .	pass	1.06
130·6 81·1	Amiens	arr. dep.	1.10 1.14
252·1 156·7	Outreau Junction	pass	2.31
253·9 157·7	La Liane Junction .	pass	2.32
297·2 184·7	Calais-Maritime	arr.	3.01

In some cases, where that *train de luxe* has to wait for some other trains, this average speed is increased to 96·1 km an hour (59·7 miles an hour) as follows on Table 7:—

TABLE 7.

Schedule of Train 67 bis (Luxe optional), Sundays, Tuesdays, Wednesdays, Fridays.

Distances from Paris.	Stations.		Time.
Km. *Miles.*			P.M.
—	Paris-Nord	dep.	12.30
50·3 31·2	Creil	pass	1.01
94·9 58·9	Breteuil branch . . .	pass	1.27
130·6 81·1	Amiens	arr. dep.	1.49 1.53
252·2 156·7	Outreau Junction . . .	pass	3.06
253·9 157·7	La Liane Junction . . .	pass	3.07
292·5 181·7	Fontinettes (slowing up)	pass	3.33
297·2 184·6	Calais-Maritime. . . .	arr.	3.49

Average speed, from end to end 94·1 km an hour (58·4 miles an hour).
Average running speed, 96·1 km (59·7 miles).

How these schedules are observed in practice may be inferred from the following remarkable instances reported on Table 8. In the first case six minutes were gained from Paris to Amiens, and the regular time kept from Amiens to Calais with two unexpected stops; 106 km (65·8 miles) exactly have been covered during the first hour of the run. The second case (train No. 67 bis), taking into account the several stoppages after the ordinary mode of calculation, shows a gain of 8 minutes. The actual running speed was 100 km an hour (62·1 miles an hour) from Paris to Calais, 297·2 km in 178 minutes (184·6 miles in 2 hours 58 minutes).

TABLE 8.

Log of Train No. 67, 14th March 1902; *Locomotive No.* 2643;
Weight, 180 *t* (177·2 *tons*).

	h.	m.	s.	
Paris (dep.)	11	52	0	(3 mins. late, on purpose.)
St. Denis	11	57	30	
Survilliers	12	10	0	
Creil	12	21	0	
Gannes	12	42	20	
Km. 101 (62·8 miles)	12	49	0	
Km. 106 (65·9 miles)	12	52	0	
Boves	1	0	0	
Slowing up at Longueau for repairs of the permanent way.				
Amiens (arr.	1	7	0	(3 mins. before time.)
Amiens (dep.	1	17	0	(3 mins. late, on purpose.)
Slowing up at Picquigny (distant signal at danger).				
Abbeville	1	45	0	
Étaples	2	11	30	
Neufchâtel	2	20	0	
Outreau	2	27	0	
Stop 1 min. at Wimille (single track), and slowing up.				
Stop 1 min. at Caffiers, by signal; dep. 2 52.				
Slowing up by signal at Calais-Maritime.				
Calais-Maritime (arr.)	3	7	0	(3 mins. late.)

Train 67 *bis*, 11*th March* 1902; *Locomotive No.* 2644;
Weight, 140 *t* (137·8 *tons*).

	h.	m.
Paris Nord (dep.)	12	30
Creil (pass)	1	1
Amiens (arr.)	1	54
Amiens (dep.)	1	58
Stop at signal No. 93		
Outreau Junction (pass)	3	[illegible]
Single track for repairs from 260 to 264 km. (161·6 to 164 miles).		
Stop at signal No. 152.		
Stop at signal No. 153.		
Calais-Maritime (arr.)	3	42

TABLE 9 (*continued on opposite page*).

Train Paris to Arras, 15*th May* 1902. *Locomotive No.* 2645.
Weight of train behind tender 178 *t* (175 *tons*).

Distances.		Stations.	Times of Passage.	Time between Stations.	Speeds. Km per hour. *Miles per hour.*	Remarks.
From Paris.	Between Stations.					
Km. *Miles.*	Km. *Miles.*		h. m. s.	m. s.		
—	—	Paris dep.	8 15 0	—	—	
	6·1 3·7			5 0	73·2 45·4	
6·1 3·7	—	St. Denis .	8 20 0	—	—	
	8·7 5·4			4 20	120·0 74·5	
14·8 9·1	—	Gonesse .	8 24 20	—	—	
	14·9 9·2			8 0	111·7 69·4	
29·7 18·4	—	Survilliers .	8 32 20	—	—	
	20·6 12·8			11 20	109·0 67·7	
50·3 31·2	—	Creil . . .	8 43 40	—	—	Slowing up.
	14·8 9·1			8 20	106·5 66·1	
65·1 40·4	—	Clermont .	8 52 0	—	—	
	14·4 8·9			7 40	112·7 70·0	
79·5 49·3	—	St. Just . .	8 59 40	—	—	
	7·8 4·8			4 0	117·0 72·7	
87·3 54·2	—	Gannes . .	9 3 40	—	—	

(continued on next page.) TABLE 9.

Train Paris to Arras, 15th May 1902. Locomotive No. 2643.
Weight of train behind tender 178 t (175 tons).

Distances.		Stations.	Times of Passage.	Time between Stations.	Speeds Km. per hour. *Miles per hour.*	Remarks.
From Paris.	Between Stations.					
Km. *Miles.*	Km. *Miles.*		h. m. s.	m. s.		
		Gannes . .	9 3 40	—	—	
100·0 62·1	23·8 14·8	Kilometre 100 (62·1 miles)	9 16 0	12 20	115·8 72·0	
111·1 69·0	—	Ailly-s-Noye	9 17 30	—	—	
	10·9 6·8			5 20	122·6 76·2	
122·0 75·8	—	Boves . .	9 22 50	—	—	
	4·0 2·5			3 20	72·0 44·7	
126·0 78·3	—	Longueau .	9 26 10	—	—	Slowing up.
	48·0 29·8			24 50	116·0 72·1	
174·0 108·1	—	Achiet . .	9 51 0	—	—	
	18·1 11·2			16 0	67·8 42·1	
192·1 119·4	—	Arras arr.	10 7 0	—	—	

REMARKS.

No very high speed when running down grade as the train was in advance of the booked time. Up gradients the admission was 50 and 65 per 100 (in high-pressure and low-pressure cylinders), the regulator full open. Steam always easily supplied by the boiler. No heating in any part of mechanism.

Water consumed, 89 litres per km. (31½ gallons per mile).

Weather, rainy.

TABLE 9 (*concluded from page* 342).

Train Arras to Paris, 16*th May* 1902. *Locomotive No.* 2645.
Weight of train behind tender 178 *t* (175 *tons*).

Distances.		Stations.	Times of Passage.	Time between Stations.	Speeds. Km. per hour. *Miles per hour.*	Remarks.
From Paris.	Between Stations.					
Km. *Miles.*	Km. *Miles.*		h. m. s.	m. s.		
192·1 119·3	—	Arras ¦ dep.	12 30 0	—	—	
	18·1 11·2			12 0	90·5 56·2	
174·0 108·1	—	Achiet . .	12 42 0	—	—	
	18·7 11·6			10 0	112·2 69·7	
155·3 96·5	—	Albert . .	12 52 0	—	—	
	29·3 18·2			17 30	110·4 62·3	
126·0 78·2	—	Longueau .	1 9 30	—	—	Slowing up.
	38·7 24·0			20 0	116·1 72·1	
87·3 54·2	—	Gannes . .	1 29 30	—	—	
	37·0 22·9			23 0	96·5 59·9	
50·3 31·2	—	Creil . . .	1 52 30	—	—	Slowing up.
	20·6 12·8			12 30	98·8 61·3	
29·7 18·4	—	Survilliers .	2 5 0	—	—	
	23·6 14·6			14 0	101·1 62·8	
6·1 3·7	—	St. Denis .	2 19 0	—	—	
	6·1 3·7			7 0	52·2 32·4	
—		Paris arr.	2 26 0	—	—	

REMARKS.

Rainy weather with south-westerly wind against the train.
Water consumed, 73 litres per km. (25·8 gallons per mile).

On the Paris-Lille line, train No. 317, which used to leave Paris at 8 p.m. and arrived at Lille at 11·7, 251 km (156 miles) in 3 hours and 7 minutes, including two stops at Arras and Douai, has been accelerated. The journey is made in 2 hours 45 minutes, or with a saving of 22 minutes, of which 18 minutes is on the running time; the weight of the train remained the same, 215 to 235 *t* (211·6 to 231 tons). Average running speed, 94·7 km an hour (58·8 miles an hour). Fig 15, Plate 37, gives the profile of the line.

On Table 9 will be found the log of two special trains which were run from Paris to Arras and from Arras to Paris on the 15th and 16th May, 1902. The average running speed was 103 km an hour (64 miles an hour); one point worthy of remark is that the speed was higher on rising gradients of 1 in 250 than on falling gradients of 1 in 250.

Fig. 16 (page 346) and Fig. 17 (page 347) reproduce indicator diagrams taken on Atlantic locomotive No 2641 during regular service. It must be noticed that horse-powers are calculated in French units of 75 kg-mètres in a second (32,550 ft.-lbs. per min.). The English horse-power is slightly different (33,000).

These examples show the large power of the new "Atlantic" compound of the Northern Railway. How the older four-cylinder compounds compare with ordinary express locomotives may be deduced from the results of a prolonged service on the Western lines, given on Table 11 (pages 349–350).

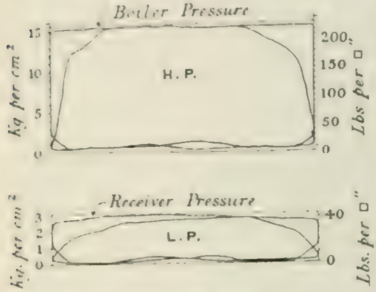
The principal dimensions of the locomotives used (series 500, 4-cylinder compounds; series 900, ordinary locomotives) are given on Table 10 (page 348):—

Fig. 16.

Diagrams taken in Regular Working on Loco. No. 2641 Nord. "Atlantic" type.
(See Fig. 1, Plate 50.)

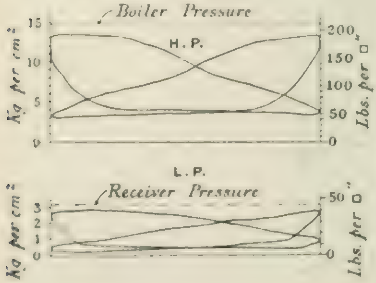
Train 179. 22 Aug. 1900.

Mean Pressures: H.P., 195·4 and 198·4 lbs. per square inch; L.P., 35 and 32 lbs per square inch.
Regulator open 80 per cent.
Admission: Full gear.
Direct exhaust of H.P. cyls. open, and direct admission to L.P. cyls.
Level.
Starting.
Weight behind tender 316·9 tons.
Pull on tender coupling 3·33 tons.



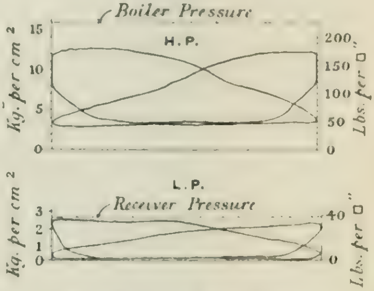
Train 179. 22 Aug. 1900.

Mean Pressures: H.P., 78 and 66·2 lbs. per square inch; L.P., 21·5 and 15·8 lbs. per square inch.
Regulator open 80 per cent.
Admission 42–63 per cent.
Level.
60·8 miles per hour.
I.H.P. (H.P. 642·5, L.P. 455·4) = 1097·9.
Weight behind tender 316·9 tons.
Pull on tender coupling 1·9 tons.



Train 112. 23 Aug. 1900.

Mean Pressures: H.P., 83·6 and 71 lbs. per square inch; L.P., 24·3 and 19·4 lbs. per square inch.
Regulator open 45 per cent.
Admission: 50–65 per cent.
Rising gradient 1 in 200.
47·8 miles per hour.
I.H.P. (H.P. 541·1, L.P. 419·2) = 960·3.
Weight behind tender 245·6 tons.
Pull on tender coupling 2·09 tons.



Train 112. 23 Aug. 1900.

Mean Pressures: H.P., 69·4 and 54 lbs. per square inch; L.P., 0·2 and 7 lbs. per square inch.
Regulator open 80 per cent.
Admission 30–65 per cent.
Level (end of falling gradient 1 in 200).
75·7 miles per hour.
I.H.P. (H.P. 684·7, L.P. 306·6) = 991·3.
Weight behind tender 245·6 tons.
Pull on tender coupling 1·08 tons.

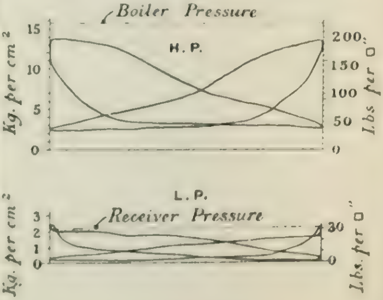
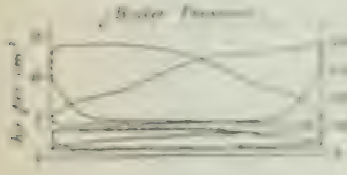


Fig. 17.

Diagrams taken in Regular Working on Loco. No. 2641, Nord. "Atlantic" type.
(See Fig. 1, Plate 10.)

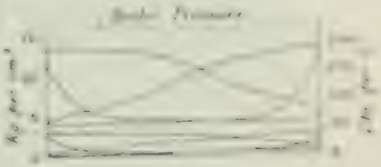
Train No. 9. 24 Aug. 1906.

Boiler pressure 227·5 lbs. per square inch.
Regulator open 80 per cent.
Admission 62 and 70 per cent.
Rising gradient 1 in 200.
Speed 63 miles per hour.
I.H.P. (H.P. 830·7, L.P. 614·1) = 1444·8.
Weight of train 219·9 tons.
Pull on tender coupling 2·20 tons.



Train No. 111. 23 Aug. 1906.

Boiler pressure 227·5 lbs. per square inch.
Regulator open 80 per cent.
Admission 45 and 67 per cent.
Falling gradient 1 in 200.
Speed 77 miles per hour.
I.H.P. (H.P. 815·4, L.P. 628·9) = 1444·3.
Weight of train 245·5 tons.
Pull on tender coupling 1·62 tons.



Train No. 179. 22 Aug. 1906.

Boiler pressure 227·5 lbs. per square inch.
Regulator full open.
Admission 50 and 65 per cent.
Rising gradient 1 in 200.
Speed 54·3 miles per hour.
I.H.P. (H.P. 744, L.P. 559·3) = 1303·3.
Weight of train 316·9 tons.
Pull on tender coupling 2·90 tons.

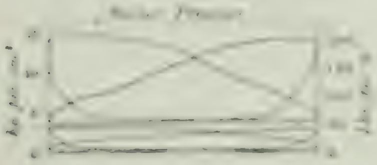


TABLE 10.

Principal dimensions of Express Locomotives, series 500 *and* 900 *of the Western Railway.*

—	Series 500. (Compound.)	Series 900. (Non-Compound.)
Boiler:		
Internal diameter . .	1·380 m (4 ft. $6\frac{3}{8}$ ins.)	1·287 m (4 ft. $2\frac{1}{16}$ ins.)
Height of axis above rail	2·485 m (8 ft. $1\frac{13}{16}$ ins.)	2·255 m (7 ft. $4\frac{3}{4}$ ins.)
Pressure . . .	14 kg per cm^2. (199·1 lbs. per sq. in.)	12 kg per cm^2. (170·6 lbs. per sq. in.)
Tubes:		
Length between plates .	3·800 m (12 ft. $5\frac{9}{16}$ ins.)	3·800 m (12 ft. $5\frac{9}{16}$ ins.)
External diameter .	70 mm ($2\frac{3}{4}$ ins.)	45 or 70 mm ($1\frac{3}{4}$ or $2\frac{3}{4}$ ins.)
Number . . .	96	197 or 88
Grate area . . .	2·40 m^2 ($25\frac{13}{16}$ sq. ft.)	2·00 m^2 ($21\frac{1}{2}$ sq. ft.)
Heating surface . .	133·70 m^2 ($1439\frac{3}{16}$ sq. ft.)	116·60 m^2 ($1255\frac{1}{8}$ sq. ft.) 100·3 m^2 ($1079\frac{11}{16}$ sq. ft.)
Cylinders:		
H.P. diameter . .	340 mm ($13\frac{3}{8}$ ins.)	460 mm ($18\frac{1}{8}$ ins.)
Stroke . . .	640 mm ($25\frac{1}{8}$ ins.)	660 mm (26 ins.)
L.P. diameter . .	530 mm ($20\frac{7}{8}$ ins.)	—
Stroke	640 mm ($25\frac{1}{8}$ ins.)	—
Driving wheels, diameter .	2·010 m (6 ft. $7\frac{1}{8}$ ins.)	2·010 m (6 ft. $7\frac{1}{8}$ ins.)
Weight in working order .	49·500 kg (48·72 tons)	46·800 kg (46 tons)
Adhesive weight . .	31·000 kg (30·51 tons)	29·500 kg (29 tons)

The 70 mm ($2\frac{3}{4}$ ins.) are Serve ribbed tubes.

TABLE 11 (*continued on next page*).

Comparative working of Compound Locomotives (Series 500) and Ordinary Locomotives (Series 900) on passenger trains between Paris and Granville.

Month	Mileage Km *Miles*	Average weight of train T. *Tons*	Coal consumed.		Oil. Gr per km *Lbs. per mile*
			Kg per km *Lbs. per mile.*	Kg per km per 100 t *Lbs. per mile per 100 tons.*	
	COMPOUND LOCOMOTIVES (SERIES 500).				
July 1901 . .	37,711 [illegible]	164 161 [illegible]	8·02 [illegible]	5·24 18·[illegible]	43·[illegible] [illegible]
August 1901 . .	38,909 [illegible]	197 193 [illegible]	9·34 [illegible]	4·74 16·[illegible]	43·[illegible] [illegible]
September 1901 .	38,464 [illegible]	158 155 [illegible]	9·02 [illegible]	5·65 [illegible]	41·8 [illegible]
Total and averages	114,084 [illegible]	173·6 [illegible]	8·90 [illegible]	5·18 [illegible]	42·9 [illegible]
	ORDINARY LOCOMOTIVES (SERIES 900).				
July 1901 . .	33,203 [illegible]	150 [illegible]	10·28 [illegible]	6·45 [illegible]	39·1 [illegible]
August 1901 . .	49,901 [illegible]	144 141 [illegible]	10·51 [illegible]	7·48 [illegible]	40·9 [illegible]
September 1901 .	41,316 [illegible]	150 [illegible]	11·09 [illegible]	7·36 [illegible]	40·4 [illegible]
Total and averages	124,512 77,[illegible]	144 [illegible]	11·16 [illegible]	7·30 [illegible]	40·9 [illegible]

Fig. 18, Plate 18, gives the profile of the Paris-Granville line.

TABLE 11 (*concluded from page* 349).

Comparative working of Compound Locomotives (Series 500) *and Ordinary Locomotives (Series* 900) *on passenger trains between Laval and Brest.*

Month.	Mileage. Km. *Miles.*	Average weight of trains. T. *Tons.*	Coal consumed.		Oil. G per km. *Lbs. per mile.*
			Kg per km. *Lbs. per mile.*	Kg per km per 100 t. *Lbs. per mile per* 100 *tons.*	
		COMPOUND LOCOMOTIVES (SERIES 500).			
July 1901 . . .	34,382 21,364·2	194 190·9	9·6 34·0	4·9 17·6	43·2 0·153
August 1901 . .	39,204 24,360·5	201 197·8	9·9 35·14	4·9 17·6	33·7 0·119
September 1901 .	40,569 25,208·7	193 189·9	9·8 34·8	5·1 18·3	32·9 0·116
Total and averages	114,155 70,933·5	196 192·9	9·8 34·8	4·96 17·8	36·6 0·129
		ORDINARY LOCOMOTIVES (SERIES 900).			
July 1901 . . .	38,426 23,877·1	166 163·3	9·6 34·0	5·8 20·9	42·3 0·150
August 1901 . .	46,457 28,865·1	158 155·5	10·2 36·2	6·5 23·4	31·4 0·111
September 1901 .	45,671 28,378·8	154 151·5	8·9 31·5	5·8 20·9	30·1 0·106
Total and averages	130,554 81,121	159·3 156·7	9·6 34·0	6·03 21·7	34·6 0·122

Fig. 19, Plate 59, gives the profile of the Laval-Brest line.

The two series of locomotives were not as identical as possible, and that would be necessary for a quite fair comparison. Still it is interesting to note that, in the long run, the compounds, with the same or with a smaller coal-consumption, have hauled greater weights, to the extent of from one-fourth to one-sixth. The oil consumption was the same in one case, and even smaller in the other.

II. *Four-Cylinder Compound Locomotives with three-coupled Axles.*

Large numbers of compound locomotives with three-coupled axles have recently been ordered in France, the total stock in use or on order being 827 on the 1st October 1903.

The 55 locomotives of this class ordered by the Northern Railway are quite similar to the previous 50, with wheels of 1·750 m (5 ft. 8¾ ins.); the dimensions will be found in Table 2 of former Paper (Proceedings, June 1900, page 404).

The Western Railway ordered 15 locomotives similar to the previous lot, the diameter of wheels being 1·720 m (5 ft. 7¾ ins.). Working fast goods traffic in comparison with the old ordinary three-coupled engines Nos. 1541–1575, the compounds have been found very economical in prolonged use, as they could haul much heavier trains with ease. The consumption of coal for 100 t (98·42 tons) carried 1 km (0·621 mile) has been reduced from 5·70 kg (12·56 lbs.) to 3·69 kg (8 lbs.) or from 1 to 0·65 (100 tons carried 1 mile with a coal-consumption from 20½ lbs. to 13¼ lbs.). The oil-consumption has been increased, but the cost of lubrication is altogether very small. The following Table gives the result of this comparative working for one year.

The principal dimensions of the locomotives used (ordinary locomotives 1541–1575, and compounds 2501–2525) are:—

TABLE 12 (*continued on opposite page*).

—	Compounds 2501–2525.	Ordinary 1541–1575.
Boiler:		
Internal diameter	1·446 m (4 ft. $8\frac{15}{16}$ ins.)	1·300 m (4 ft. $3\frac{3}{16}$ ins.)
Height of axis above rail	2·410 m (7 ft. $10\frac{7}{8}$ ins.)	2·055 m (6 ft. $8\frac{11}{16}$ ins.)
Working pressure	14 kg per cm². (199·1 lbs. per sq. in.)	9 kg per cm². (128 lbs. per sq. inch.)
Tubes:		
Length between plates	4·300 m (14 ft. $1\frac{5}{16}$ ins.)	4·300 m (14 ft. $1\frac{5}{16}$ ins.)
External diameter	70 and 45 mm. ($2\frac{3}{4}$ and $1\frac{3}{4}$ inches)	49 mm ($1\frac{15}{16}$ ins.)
Number	117 4 of 45 mm ($1\frac{3}{4}$ ins.) 113 Serve	198
Grate area	2·38 m² ($25\frac{5}{8}$ sq. ft.)	1·42 m² ($15\frac{1}{4}$ sq. ft.)
Heating surface	187·97 m² ($2023\frac{3}{8}$ sq. ft.)	139·50 m² ($1501\frac{5}{8}$ sq. ft.)
Cylinders, H.P.:		
Diameter	350 mm ($13\frac{3}{4}$ ins.)	460 mm ($18\frac{1}{8}$ ins.)
Stroke	640 mm ($25\frac{1}{8}$ ins.)	640 mm ($25\frac{1}{8}$ ins.)
Cylinders, L.P.:		
Diameter	550 mm ($21\frac{5}{8}$ ins.)	—
Stroke	640 mm ($25\frac{1}{8}$ ins.)	—
Driving wheels, diameter	1·720 mm (5 ft. $7\frac{11}{16}$ ins.)	1·510 m (4 ft. $11\frac{7}{16}$ ins.)
Weight in working order:		
Total	58·4 t (57·48 tons)	36·45 t (35·87 tons)
Adhesive	41·5 t (40·84 tons)	

Continued on next page | TABLE 12

Comparative working of Compounds 2501–2525 and Ordinary Locomotives 1541–1575 on fast goods trains between Le Havre and Argenteuil or Batignolles

Month.	Mileage. Km. *Miles.*	Average weight of train. T. *Tons.*	Coal consumed. Kg per km. *Lbs. per mile.*	Coal consumed. Kg per km per 100 t *Lbs. per mile per 100 tons.*	Oil. G per km. *Lbs. per mile.*	Number of minutes saved.
	ORDINARY LOCOMOTIVES 1541–1575					
May 1899	[illegible] [illegible]	284 [illegible]	[illegible] [illegible]	[illegible] [illegible]	26·6 [illegible]	4,110
June „	[illegible] [illegible]	287 [illegible]	14·6 [illegible]	5·77 [illegible]	[illegible] [illegible]	4,813
July „	38,607 [illegible]	287 [illegible]	[illegible] [illegible]	4·81 [illegible]	[illegible] 0·099	4,205
August „	[illegible] 23,700	281 [illegible]	14·2 [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible]
September „	[illegible] [illegible]	[illegible] [illegible]	14·1 [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible]
October „	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	6,687
November „	37,474 [illegible]	282 277½	17·3 [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible]
December „	42,971 [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	25·1 0·089	[illegible]
January 1900	[illegible] [illegible]	283 [illegible]	[illegible] [illegible]	6·48 [illegible]	25·3 [illegible]	[illegible]
February „	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] 0·089	[illegible]
March „	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible]
April „	[illegible] [illegible]	272 [illegible]	[illegible] [illegible]	[illegible] [illegible]	[illegible] 0·092	4,614
Totals and averages	[illegible] [illegible]	[illegible] [illegible]	16·1 [illegible]	5·70 [illegible]	[illegible] 0·097	57,935

TABLE 12 (*concluded from page* 352).

Comparative working of Compounds 2501–2525 *and Ordinary Locomotives* 1541–1575 *on fast goods trains between Le Havre and Argenteuil or Batignolles.*

Month.	Mileage. Km. *Mile.*	Average weight of train. T. *Tons.*	Coal consumed.		Oil. G per km. *Lbs. per mile.*	Number of minutes saved.
			Kg per km. *Lbs. per mile.*	Kg per km per 100 t. *Lbs. per mile per 100 ton.*		
			Compound Locomotives 2501–2525.			
May 1899	26,503 16,468	445 438	16 56·8	3·61 13	50 0·177	3,763
June ,,	28,758 17,870	442 435	14·9 53	3·37 12·1	50·7 0·179	3,886
July ,,	37,847 23,516	409 402½	11·3 40	2·76 9·9	52·2 0·185	5,050
August ,,	40,702 25,291	410 403½	13·9 49·3	3·39 12·2	51·5 0·182	5,547
September ,,	37,867 23,528	432 425	14·7 52·1	3·39 12·2	53 0·188	5,839
October ,,	44,946 27,928	390 383¾	15 53·2	3·85 13·8	50 0·177	9,213
November ,,	46,923 29,157	387 380¾	16·3 57·8	4·22 15·3	50·2 0·178	9,539
December ,,	50,619 31,472	407 400½	17·8 63·1	4·39 15·8	53·4 0·189	11,467
January 1900	39,611 24,614	449 442	17·8 63·1	3·98 14·3	47·1 0·167	5,399
February ,,	37,029 23,009	455 447¾	17·6 62·4	3·88 14	46·2 0·164	4,877
March ,,	42,667 26,513	474 466½	16·9 60	3·57 12·8	48·2 0·171	5,592
April ,,	39,335 24,442	472 464½	16·4 58·2	3·47 12·5	48·2 0·171	5,236
Totals and averages	472,837 293,808	431 424	15·7 55·7	3·69 13·3	50·7 0·179	75,408

Fig. 20, Plate 60, gives the profile of the Paris-Le Hâvre line.

In addition, the Western Railway ordered 20 six-coupled compound locomotives with diameter of wheels enlarged to 1·910 m. (6 ft. 3 3/16 ins.) (Nos. 2701–2720), this enlargement being the only important difference with the preceding lot, Fig 2, Plate 50. The principal dimensions are given on Table 13:—

TABLE 13.

Principal dimensions of Western Railway Compounds, Nos. 2701–2720.

Boiler:	
Internal diameter . .	1·480 m (4 ft. 10¼ ins.)
Height of axis above rail . .	2·305 m (7 ft. 6¾ ins.)
Working pressure . . .	15 kg per cm² (213·4 lbs. per sq. in.)
Tubes:	
Length between plates . . .	4·500 m (14 ft. 9 3/16 ins.)
External diameter . . .	70 & 45 mm (2¾ & 1¾ ins.)
Number, 4 of 45 mm (1¾ ins.)	
113 Serve of 70 (2¾ ins.) . .	117
Grate area	2·45 m² (26⅓ sq. ft.)
Heating surface . . .	202 m² (2174·3 sq. ft.)
Cylinders, H.P.:	
Diameter	350 mm (13¾ ins.)
Stroke	640 mm (25 3/16 ins.)
Cylinders, L.P.:	
Diameter	530 mm (20⅞ ins.)
Stroke	640 mm (25 3/16 ins.)
Driving wheels, diameter . .	1·910 m (6 ft. 3 3/16 ins.)
Weight in working order:	
Total	63·5 t (62·5 tons)
Adhesive	45 t (44·29 tons)

Interesting tests have been made between Paris and Le Mans of one of these new locomotives (No. 2701); one six-coupled compound with smaller wheels 1·720 m (5 ft. 7¾ ins.) (No. 2516); one four-coupled express compound (No. 521), and an Italian six-coupled compound locomotive (No. 3701), with the fire-box at the leading end, which was exhibited at Paris in 1900. These four engines hauled successively the same express trains from Paris to Le Mans, the distance being 217·5 km (135·15 miles) and back. The profile of the line is given in Fig. 21, Plate 61. The principal dimensions of the four engines are given on Table 14 (page 356):—

TABLE 14.

No. of Locomotive.	2701	2516	521	3701 (Italian)
Grate area	2·45 m². (*$26\frac{3}{8}$ sq. ft.*)	2·45 m². (*$26\frac{3}{8}$ sq. ft.*)	2·40 m². (*$25\frac{13}{16}$ sq. ft.*)	3 m². (*$32\frac{5}{16}$ sq. ft.*)
Heating surface . . .	202 m². (*$2174\frac{5}{16}$ sq. ft.*)	194 m². (*$2088\frac{1}{4}$ sq. ft.*)	133·7 m². (*$1439\frac{3}{16}$ sq. ft.*)	165 m². (*$1776\frac{1}{8}$ sq. ft.*)
Working pressure . . .	15 kg per cm². (*213·3 lbs. per sq. in.*)	14 kg per cm². (*199 lbs. per sq. in.*)	14 kg per cm². (*199 lbs. per sq. in.*)	15 kg per cm². (*213·3 lbs. per sq. in.*)
Diam. of cylinders : H.P. .	350 mm. (*$13\frac{3}{4}$ ins.*)	350 mm. (*$13\frac{3}{4}$ ins.*)	340 mm. (*$13\frac{3}{8}$ ins.*)	380 mm. (*15 ins.*)
" " " L.P. .	550 mm. (*$21\frac{5}{8}$ ins.*)	550 mm. (*$21\frac{5}{8}$ ins.*)	530 mm. (*$20\frac{7}{8}$ ins.*)	570 mm. (*$22\frac{7}{16}$ ins.*)
Stroke of pistons . . .	640 mm. (*$25\frac{1}{8}$ ins.*)	640 mm. (*$25\frac{1}{8}$ ins.*)	640 mm. (*$25\frac{1}{8}$ ins.*)	650 mm. (*$25\frac{9}{16}$ ins.*)
Diameter of driving wheels .	1·910 m. (*6 ft. $3\frac{3}{16}$ ins.*)	1·720 m. (*5 ft. $7\frac{11}{16}$ ins.*)	2·010 m. (*6 ft. $7\frac{1}{8}$ ins.*)	1·940 m. (*6 ft. $4\frac{3}{8}$ ins.*)
Adhesive weight . . .	45 t. (*44·28 tons*)	41·5 t. (*40·84 tons*)	31 t. (*30·51 tons*)	43·5 t. (*42·81 tons*)

It will be noticed that the production of steam per kg (lb.) of coal is small with the No. 521 engine, owing to its rather limited heating surface as compared to the grate area, this surface being equal to only 56 times the grate area. The proportion is better in the other engines.

The Paris-Orleans Railway has received from the "Société Alsacienne de Constructions Mécaniques" 15 six-coupled locomotives (Nos. 4001–4015), Fig. 6, Plate 51, with wheels of 1·800 m (5 ft. $10\frac{7}{8}$ ins.), fitted with a large boiler identical to the one of the new "Atlantic" locomotives of the same company. The size of the cylinders is also the same, 360 and 600 by 640 mm ($14\frac{3}{16}$ and $23\frac{5}{8}$ by $25\frac{3}{16}$ ins.). The total weight in service is 73,800 kg ($72\frac{5}{8}$ tons), of which 53,400 are adhesive.

The Southern Railway made an important addition of 48 engines to their stock of 27 six-coupled 4-cylinder compounds, without altering the type. The P.L.M. ordered 100 such new locomotives.

Since January 1900, the Eastern Railway, which had then 60 such locomotives (Nos. 3401–3460), ordered 152 new ones. Of these, the Nos. 3461–3500 were very nearly similar to the previous engines; however, the fire-box was made deeper in front, to give room for a more inclined grate. For locomotives Nos. 3501–3520 (Fig. 8, Plate 50, and Fig. 9, Plate 52), and Nos. 3521–3550, 3551–3580, 3581–3610, a new starting gear (the same as on the Northern Railway locomotives) was substituted to the old one (shown on Fig. 24, Plate 50, Proceedings of the Institution for June 1900). The driver is on the left side of the engine. The bogie was modified, inside boxes being substituted for the outside ones. Engines Nos. 3501–3520 and 3581–3610 have piston-valves.

The two six-coupled locomotives Nos. 3101–3102 of the Eastern Railway have large wheels, and are intended for express trains, Fig. 10, Plate 53. They were put in service at the end of 1902. The principal dimensions are given on Table 16 (page 362) :—

TABLE 15 (*continued on next page*).

Consumption of Coal and Water of Western Railway Engines
working Trains Nos. 5 and 30

1st.—Train 5. Paris St. Lazare to

Dates.	Numbers of Engines.	Number of Carriages and of Axles.	Weight of Train, including Passengers and Luggage.	Consumption of Coal.			Consumption of Water.			Water evaporated. Litres per Kg of Coal.
				Total.	Kg per Km.	Kg per Km per 100 t.	Total.	Litres per Km.	Litres per Km per 100 t.	
			Tonnes. *Tons.*	Kg. *Lbs.*	*Lbs. per mile.*	*Lbs. per mile per 100 tons.*	Cubic mètres. *Gals.*	*Gals. per mile.*	*Gals. per mile per 100 tons.*	*Lbs. per lb. of coal.*
1902 22 April	2701	21 c. 47 a.	280 275·57	3,150 6,944·5	14·48 51·4	5·17 18·6	23,217 5,110	106·7 37·8	38·1 13·7	7·37 7·3
1901 23 January	521	16 c. 38 a.	220 216·52	3,800 8,377·5	17·47 62·0	7·94 28·6	19,668 4,329	90·4 32·1	41·1 14·8	5·17 5·15
25 January	2516	16 c. 38 a.	225 221·44	3,350 7,385·4	15·40 54·67	6·84 24·6	20,382 4,486	93·7 33·2	41·6 15·0	6·084 6·06
21 January	3701	16 c. 38 a.	225 221·44	3,550 7,826·3	16·32 57·9	7·25 26·1	21,950 4,831	100·9 35·8	44·8 16·1	6·18 6·1

(continued on next page) TABLE 15.

Nos. 2701, 521, 2516, *and of Italian Engine No.* 3701,
between Paris and Le Mans.

Le Mans. 217·5 Km (135·15 *miles*).

Number of Minutes taken.		Average running speed.	Results observed in dynamometer car.		Coal consumption.				Water consumed.		Minutes.		State of Weather.
					Per square mètre of grate during *Per square foot of grate during*		Per 1 hour and 1 horse-power on tender coupling during		Per 1 hour and 1 horse-power on tender coupling during				
From start to stop.	Whilst running.		Average pull on tender coupling.	Average horse-power on tender coupling.	Total time.	Actual running time.	Total time.	Actual running time.	Total time.	Actual running time.	Gained.	Lost.	
		Km. *Miles.*	Kg. *Tons.*	H.P.	Kg. *Lbs.*	Kg. *Lbs.*	Kg. *Lbs.*	Kg. *Lbs.*	Litres. *Gals.*	Litres. *Gals.*			
204	182	71·7 44·5	2,106 2·07	558	386 79·05	432·6 88·57	1·660 3·659	1·86 4·10	12·23 2·69	13·68 3·01	18½	—	Rain, light side wind.
203	195	66·7 41·4	1,359 1·33	334	468 95·85	487·1 99·73	3·27 7·20	3·51 7·73	17·4 3·83	18·11 3·99	5	—	Somewhat strong side wind.
207	198	65·9 40·9	1,474 1·45	346·6	396 81·10	414·3 84·79	2·79 6·15	2·92 6·43	16·8 3·70	17·81 3·92	7	—	Somewhat strong side wind.
204	192	67·9 42·1	1,800 1·77	430·4	348 71·27	369·7 75·57	2·42 5·33	2·57 5·66	14·94 3·29	15·9 3·50	10	—	Rain and somewhat strong side wind.

TABLE 15 (*concluded from page* 358).

Consumption of Coal and Water of Western Railway Engine
working Trains Nos. 5 and 3

2nd.—Train 30. Le Mans to Pari

Dates.	Numbers of Engines.	Number of Carriages and of Axles.	Weight of Train, including Passengers and Luggage.	Consumption of Coal.			Consumption of Water.			Water evaporated. Litres per Kg of Coal.
				Total.	Kg per Km.	Kg per Km per 100 t.	Total.	Litres per Km.	Litres per Km per 100 t.	
			Tonnes. *Tons.*	Kg. *Lbs.*	*Lbs. per mile.*	*Lbs. per mile per 100 tons.*	Cubic mètres. *Gals.*	*Gals. per mile.*	*Gals. per mile per 100 tons.*	*Lbs. per lb. of coal.*
1902 23 April	2701	24 c. 48 a.	250 246	2,600 5,732	11·95 42·42	4·78 17·2	21,000 4,621	96·5 34·2	38·6 13·9	8·40 8·4
1901 24 January	521	23 c. 46 a.	240 236·2	3,450 7,606	15·86 56·32	6·6 23·8	19,016 4,185	87·4 31·0	39·7 14·3	5·51 5·5
26 January	2516	23 c. 46 a.	245 241·12	3,300 7,275·2	15·17 53·35	6·2 22·3	20,948 4,610	96·2 34·1	39·2 14·1	6·34 6·3
22 January	3701	24 c. 48 a.	260 255·89	3,200 7,054·7	14·71 52·22	5·66 20·4	23,015 5,065	105·8 37·5	40·7 14·6	7·19 7·1

(*concluded from page* 358) TABLE 15.

Nos. 2701, 521, 2516, *and of Italian Engine No.* 3701, *between Paris and Le Mans.*

St. Lazare. 217·5 Km (135·15 *miles*).

Number of Minutes taken.		Average running speed.	Results observed in dynamometer car.		Coal consumption.				Water consumed.		Minutes.		State of Weather.
					Per square mètre of grate during *Per square foot of grate during*		Per 1 hour and 1 horse-power on tender coupling during		Per 1 hour and 1 horse-power on tender coupling during				
From start to stop.	Whilst running.		Average pull on tender coupling.	Average horse power on tender coupling.	Total time.	Actual running time.	Total time.	Actual running time.	Total time.	Actual running time.	Gained.	Lost.	
		Km. *Miles.*	Kg. *Tons.*	H.P.	Kg. *Lbs.*	Kg. *Lbs.*	Kg. *Lbs.*	Kg. *Lbs.*	Litres. *Gals.*	Litres. *Gals.*			
252	223	58·5 36·3	1,698 1·67	366	257·9 52·82	291·4 59·69	1·69 3·72	1·91 4·21	13·2 2·91	15·42 3·40	13	—	Fine weather, with light side wind.
247	219	59·5 36·9	1,693 1·66	320·3	348 71·27	393·8 [illegible]	2·58 5·68	2·95 6·50	14·4 3·17	16·26 3·58	5	—	Fine weather, with frost.
248	218	59·8 37·1	1,615 1·58	305·3	324 66·36	370·7 75·76	2·52 5·53	2·97 6·54	16·62 3·66	18·89 4·16	9	—	Fine weather, with frost.
244	211	61·8 38·4	1,687 1·66	340	258 52·84	303·3 62·15	2·28 5·02	2·67 5·88	16·20 3·57	19·24 4·24	16	—	Fine weather.

TABLE 16.

Principal dimensions of Eastern Railway Locomotives, Nos. 3101–3102.

Boiler:	
Internal diameter	1·550 m (5 ft. 1 in.)
Height of axis above rail	2·630 m (8 ft. 7½ ins.)
Working pressure	15 kg per cm² (213 lbs. per sq. in.)
Tubes:	
Length between plates	4·200 m (13 ft. 9⅜ ins.)
External diameter	70 mm (2¾ ins.)
Number	140
Grate area	2·857 m² (30¾ sq. ft.)
Heating surface	223·94 m² ($2410\frac{7}{16}$ sq. ft.)
Cylinders, H.P.:	
Diameter	350 mm (13¾ ins.)
Stroke	660 mm (26 ins.)
Cylinders, L.P.:	
Diameter	560 mm (22 ins.)
Stroke	660 mm (26 ins.)
Driving wheels, diameter	2·090 m (6 ft. $10\frac{5}{16}$ ins.)
Weight in working order:	
Total	71·8 t (70·66 tons).
Adhesive	51 t (50·19 tons).

It is interesting to mention here a tandem compound locomotive, which has been built recently by the Northern Railway Company for working passenger trains on the Ceinture Railway of Paris. This railway is a circular line round Paris, with a length of 31·5 km (19½ miles), 23 stations, and gradients of 1 in 100. In order to avoid an undue loss of time, ordinary locomotives must run in full gear until the regular speed is attained; thence results a large steam consumption, and, in addition, the too-powerful blast disturbs the fire on the grate.

The use of a compound locomotive, under these circumstances, goes against the prevailing opinion that this class of engine is not fit for frequently-stopping trains. And really it seems that compounds, with cylinders of suitable proportions, will give less trouble and consume less steam when worked in full gear for a prolonged time. This point is discussed at the end of the present Paper. The new locomotive, one of a lot of 15, is shown on Fig. 4, Plate 50. The principal dimensions are given on Table 17. The valves of both H.P. and L.P. cylinders are driven by the same spindle, but this spindle is interrupted in its middle part, between the two tandem cylinders, and the motion is transmitted from the rear or H.P. part to the front or L.P. one by a connection that is not tight, but leaves a longitudinal play of a few millimètres. Owing to this device, the L.P. valve is always a little later in its travel than the H.P. valve, thus producing more admission and less compression in the L.P. cylinder

TABLE 17.

Tank Locomotives Nos. 51–65 for the Ceinture Railway of Paris.

Weight, empty		50·839 t (50 tons).
Water in boiler		3,665 l (806·9 gallons).
Coal in bunkers		3,000 kg (6613·8 lbs. or 2·95 tons).
Water in tanks		5,000 l (1100·23 gallons).
Total weight, in running order		63·198 t (62·19 tons).
Adhesive weight, maximum		47·763 t (47 tons).
,, ,, with half water and coal		42·700 t (42 tons).
Mean diameter of boiler		1·316 m (4 ft. 3$\frac{13}{16}$ ins.)
Working pressure		16 kg per cm² (227·6 lbs. per sq. in.)
Number of Serve tubes		98
Length of tubes		3·500 m (11 ft. 5$\frac{13}{16}$ ins.)
External diameter of tubes		70 mm (2¾ ins.)
Heating surface:		
Fire-box		10·23 m² (110⅛ sq. ft.)
Tubes		127·70 m² (1,374½ sq. ft., internal).
Total		137·93 m² (1,484¾ sq. ft.)
Area of grate		2·27 m² (24$\frac{7}{16}$ sq. ft.)
Diameter of H.P. cylinders		330 mm (13 ins.)
,, ,, L.P. cylinders		540 mm (21¼ ins.)
Stroke of pistons		600 mm (23⅝ ins.)
Diameter of coupled wheels		1·600 m (5 ft. 2$\frac{15}{16}$ ins.)
Diameter of bogie wheels		0·850 m (2 ft. 9½ ins.)
Extreme distance of axles		7·900 m (25 ft. 11 ins.)
Total length of engine		11·445 m (37 ft. 6½ ins.)
Width of engine		2·900 m (8 ft. 6$\frac{3}{16}$ ins.)
Tractive power:		
Working compound	theoretical	10,205 kg (10·04 tons).
	practical (70 per 100)	7,144 kg (7·03 tons).
With direct admission to L.P. cylinders	theoretical	13,095 kg (12·88 tons).
	practical (70 per 100)	9,166 kg (9·02 tons).

The first results obtained with these locomotives gave satisfaction. The whole circuit has been made in one hour and five minutes, stoppages included. The present schedule allows at least one hour and twenty minutes.

III. *Four-cylinder Compound Locomotives with Four-coupled Axles.*

Although in many cases the six-coupled 4-cylinder compounds have replaced with advantage the old eight-coupled locomotives, which were largely used in France, the P.L.M. system has a large number of such engines with four cylinders, and a new type of eight-coupled 4-cylinder compound has been built by the Southern Railway, and by the Eastern Railway.

This last engine is represented by Fig. 7, Plate 51, and Fig. 11, Plate 53. A pony truck is used in front of the cylinders; Fig. 12, Plate 54, gives the detail of this truck. The four cylinders are placed on a line under the smoke-box. The high-pressure cylinders are inside, and command the second coupled axle. The low-pressure cylinders are connected with the third axle. It is advisable, as far as possible, to put the low-pressure cylinders inside, under the smoke-box; but in this case their diameter is too large, and they cannot be placed between the frames.

The principal dimensions are as given in Table 18 (page 365):—

A description, with drawings, of the eight-coupled locomotive of the Southern Railway has been published in the "Revue générale des Chemins de fer et des Tramways" (April 1902), and in "Engineering" (4th and 18th July, 1902). Tables of comparative experiments of these new engines and of old goods engines show an important economy in favour of the compound. The results of comparative working for twelve days are shown in Table 19 (page 366).

The old locomotive (No. 2001) had a grate area of $1 \cdot 900$ m^2 ($20 \cdot 4$ square feet), a working pressure of 9 kg per cm^2 (128 lbs. per square inch), cylinders of 540 mm ($21\frac{1}{4}$ inches) by 610 mm (24 inches), wheels of $1 \cdot 210$ m (3 feet $11\frac{5}{8}$ inches), and weighs 54 t ($53 \cdot 14$ tons). With the new ones, the weight of the train was increased from 120 t ($118 \cdot 10$ tons) to 170 t ($167 \cdot 31$ tons), the coal-consumption being slightly reduced, and the quantity of water consumed remaining practically the same.

The Paris-Orléans Railway has completed its stock of powerful locomotives with 12 engines of this class (four coupled axles and a pony truck); the boiler is the same as on the new "Atlantic" and six-coupled engines, mentioned above.

TABLE 18.

Locomotives with Four-coupled Axles.

—	Southern Railway.	Eastern Railway.
Boiler :		
Internal diameter . .	1·513 m (4 ft. 11½ ins.)	1·550 m (5 ft. 1 in.)
Height of axis above rail	2·600 m (8 ft. 6⅜ ins.)	2·600 m (8 ft. 6⅜ ins.)
Working pressure . .	15 kg per cm² (213 lbs. per sq. in.)	15 kg per cm² (213 lbs. per sq. in.)
Tubes :		
Length between plates .	4·300 m (14 ft. 1 5/16 in.)	4·300 m (14 ft. 1 5/16 ins.)
External diameter .	70 mm (2¾ ins.)	70 mm (2¾ ins.)
Number . . .	148	148
Grate area . .	2·808 m² (30¼ sq. ft.)	2·707 m² (29⅛ sq. ft.)
Heating surface . .	256·21 m². (2757⅞ sq. ft.)	248·15 m². (2671⅛ sq. ft.)
Cylinders, H.P. :		
Diameter . . .	390 mm (15⅜ ins.)	390 mm (15⅜ ins.)
Stroke . . .	650 mm (25 9/16 ins.)	650 mm (25 9/16 ins.)
Cylinders, L.P. :		
Diameter . . .	600 mm (23⅝ ins.)	600 mm (23⅝ ins.)
Stroke . . .	650 mm (25 9/16 ins.)	650 mm (25 9/16 ins.)
Diameter of driving wheels	1·400 m (4 ft. 7 1/16 ins.)	1·400 m (4 ft. 7 1/16 ins.)
Weight in working order :		
Total . . .	71·6 t (70·46 tons)	72·5 t (71·64 tons)
Adhesive . . .	64·6 t (63·57 tons)	65·3 t (64·26 tons)

TABLE 19.

Section of Line.	Distances. Km. *Miles.*	Average weight of train (exclusive of locomotive and tender). *Tons.*	Consumption of Coal.			Water Evaporated.		Profile.
			Total. Kg. *Lbs.*	Kg per km of train. *Lbs. per mile.*	Kg per km per 100 t. *Lbs. per mile per 100 tons.*	Total. Cubic mètres. *Gallons.*	Per kg of coal.	
			LOCOMOTIVE 4001 (COMPOUND).					
Aguessac to Engayresque	15·2	170	4,676	51,271	30,159	36,472		Rise 33 mm. per m. 1 in 30.
	9·4	167·3	10,308	182·0	108·8	8,027		
Engayresque to Sévérac	8·9	170	540	10,112	5,918	5,221		Fall 33 mm. per m. 1 in 30.
	5·5	167·3	1,190·4	36·0	21·45	1,149		
Totals and averages . .	24·1	170	5,216	30,691	18,053	41,693	7·79 l =	
	14·9	167·3	11,499	109	65·11	9,176	7·78 *lbs. per lb. of coal*	
			LOCOMOTIVE 2001 (NON-COMPOUND).					
Aguessac to Engayresque	15·2	120	5,190	56,907	47,423	37,089		
	9·4	118	11,441	202·0	171·08	8,162		
Engayresque to Sévérac	8·9	120	450	8,426	7,022	4,782		
	5·5	118	992	29·8	25·29	1,052·7		
Totals and averages . .	24·1	120	5,640	32,666	27,222	41,871	7·14 l =	
	14·9	118	12,433	115·9	98·16	9,215·7	7·13 *lbs. per lb. of coal*	

IV. *Valve Gears for Compound Locomotives.*

As regards valve gears, the Walschaerts system has been adopted for many of the French 4-cylinder compounds, as well as for ordinary locomotives.* This system is quite convenient when the valve is placed above or under the cylinder, and there is a distinct advantage in the use of one eccentric instead of two, for inside as well as for outside cylinders. The whole mechanism is simple, and easily kept in order. The distribution of steam effected by the Walschaerts system is particularly good, and quite uniform on both sides of piston at different points of cut-off. The reason of this uniformity, greater than with the ordinary systems, where the whole motion is derived from two eccentrics, is obvious; with the ordinary systems, the obliquity of the connecting-rod is a cause of inequality, the travel of piston, for a same angular displacement of the crank from both dead points, showing noticeable differences. With the Walschaerts gear, the motion of the valve is derived from one eccentric and from the piston itself; the obliquity of the connecting-rod has no effect, and inequalities arise only from the small obliquity of the eccentric rod.

Plate 62 gives details of the newest construction of this gear by the Société Alsacienne de Constructions Mécaniques. Fig. 26 shows the oscillating link, supported by trunnions on both sides; Figs. 27 to 29 show the way of guiding the valve-spindles. With the ordinary design of the Walschaerts gear there is no vertical plane of symmetry for the whole mechanism, and that want of symmetry tends to produce lateral bending of the parts. Fig. 27 shows how the lever, worked from the piston crosshead and from the link, is connected to the valve-spindle, the connection being made on the central axis of the spindle, which is guided in straight line by a forked part. On Figs. 28 and 29 are seen the guides of this forked part for the H.P. (outside) and L.P. (inside) cylinders.

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* An interesting history of the Walschaerts gear, by Mr J. Boulvin, has been published in the "Revue de Mécanique," February 1902, page 105.

Some contrivances are necessary to avoid excessive compression in compound locomotives. A much larger clearance than usual must be resorted to. On the Eastern Railway locomotives, this clearance is about 18 per cent. of the cylinder capacity proper (stroke × surface of piston) for the high-pressure cylinders, and 12 per cent. for the low-pressure cylinders. On the Southern Railway locomotives, the clearance is from 12 to 14 per cent. for the high-pressure, and from 7 to 9 per cent. for the low-pressure cylinders. In addition, the valves have generally a negative lap of about 1·5 mm (0·06 inch or $\frac{1}{16}$ inch) on each side. On the Eastern locomotives, this negative lap is given to the low-pressure valves only. It must be noticed that short cut-off is not resorted to, especially at high speed. When these precautions are taken, experience proves that the highest speeds may be obtained with compounds as well as with ordinary locomotives.

Experiments made on the Northern Railway* have proved that it is useful to give a large diameter to the pipes supplying steam to the high-pressure cylinders; as the regulator is not always wide open, and as the density of steam at very high pressure is great, it might be supposed that a small pipe would be sufficient; but too small a pipe causes an important drop of pressure during the admission in the high-pressure cylinder, shown on the diagrams, and this is avoided with a large pipe. A diameter of 90 mm ($3\frac{1}{2}$ inches) is advisable, the diameter of the cylinders being 340 mm ($13\frac{3}{8}$ inches) or 350 mm ($13\frac{3}{4}$ inches), and each cylinder being provided with a separate pipe.

Fig. 30, Plate 63, shows the joint, inside the boiler, of the steam-pipe, running from the regulator to a casting where it branches in two pipes, giving steam to the H.P. cylinders. On Fig. 31 is seen the sliding joint of one of these branch pipes. The way of making joints with very narrow annular portions of spherical surface is noticeable on these illustrations.

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* *See* "Revue générale des Chemins de fer et des Tramways," June 1898 page 431.

V. *Starting Devices.*

In all recent 4-cylinder compound locomotives, it has been found advisable to provide a direct exhaust for the high-pressure cylinders, with an admission of steam from the boiler (at a reduced pressure) to the low-pressure cylinders. The object of such device is principally to avoid any difficulty in starting from rest, such as occurs sometimes with the ordinary locomotives, and specially with compounds without such apparatus. In exceptional cases, for instance in taking a heavy goods train at a slow speed up a grade, the separate working of the four cylinders may be resorted to; but generally the adhesion would be found insufficient for such prolonged working.

The latest style of this device is shown on Fig. 32, Plate 63, and consists of a revolving lantern on the side of the steam-chest of the low-pressure cylinder (one for each cylinder). Steam exhausts from the H.P. cylinder through the pipe on the left of the drawing, and passes through L and O into the steam-chest of the L.P. cylinder. In another position, the opening O is covered, and L^1, communicating with O^1, opens a direct exhaust to the H.P. cylinder. At the same time, a special valve, Fig. 33, on the back plate of the boiler, admits live steam to the L.P. cylinder. This valve does not need to be of large section, as the pressure of steam must be reduced, a safety-valve on the receiver (in communication with the L.P. steam-chests) blowing off under a pressure of 6 kg per cm^2 (85·3 lbs. per sq. in.); the top pipe seen on Fig. 33 takes dry steam in the dome, the bottom one sends it to the receiver; the valve is a double one, to allow a fine regulation of pressure; the small valve seen on the top of the casting is for heating purposes. The revolving lantern is worked with the aid of a compressed-air cylinder.

The starting device allows four different ways of using the engine: (1) normal compound working; (2) with four separate cylinders, for rapid starting, used in very special cases; (3) with H.P. cylinders only; or (4) with L.P. cylinders only, in case of breakdown of mechanism.

VI. *Setting of Cranks.*

In all recent designs, the simple plan of setting at 180° the two cranks on each side of the engine has been adopted: thus the left-hand side outside crank and the left inside crank are at 180°, whilst the right cranks are at 90° with these. Of course a more complete equilibrium, without the use of counterweights on the wheels, might be obtained by setting the cranks after the Yarrow, Schlick, and Tweedy system. The angles of setting are very easily determined by the application of the method beautifully described before the Institution by Professor Dalby.* But as the outside cranks corresponding to the high-pressure cylinders must be at right angles, owing to the coupling-rod, the inside cranks would be at an angle of about 70°; as they correspond to the low-pressure cylinders, this would give an irregular exhaust, which would not be very satisfactory, at least in appearance.

VII. *Superheated Steam.*

Nothing worth mention has yet been done in France as regards the use of superheated steam on locomotives. In England, Mr. Aspinall's superheater has been described in the Proceedings of the Institution (June 1900, page 409). In Germany, several applications of superheated steam have been made, and fully described by Mr. Garbe.† Mr. Garbe's conclusion is that fully as good results, as regards economy of fuel or increase of power of locomotive, may be obtained by superheating as by compounding. The use of superheating has not been in use long enough to decide the question with certainty, from a practical point of view; and experiments remain to be done on the effect of superheating on compound locomotives. It is a question of great interest, but beyond the scope of the present Paper.

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* Proceedings 1901, Part 5, page 1157.

† Zeitschrift des Vereines deutscher Ingenieure, 1902, pages 145 and 189.

VIII. *Some Details of Construction.*

The reversing gear more generally used is that shown on Fig. 22, Plate 49 (Proceedings, June 1900), with two screws in a line, which can be worked separately or together. On the latest locomotives of the P.L.M. system, the design, Fig. 34, Plate 61, is such that the reversing gear of the L.P. cylinders is always in full gear, forwards or backwards; the position of the H.P. gear alone can be altered at will. An oil cataract, seen on the right of the drawing, is connected with the L.P. bar, to avoid too rapid motion when the gear is reversed, as this bar is only pushed by the movable nut on the screw but not firmly connected with this nut.

For easy working of the ordinary gear, the Société Alsacienne has recently provided two ball bearings at the forward end of the screw shaft, Fig. 35; these consist of small balls between two grooved plates, of an ordinary type, which can be easily and cheaply replaced when worn out.*

The piston-valves of Est engines, Nos. 3501–3520, have already been mentioned; Fig. 36 shows the valves for H.P. cylinders, and Fig. 37 the valves on L.P. cylinders. Admission is between the pistons of the valves and exhaust outside. They have been found advantageous, principally as providing larger steam passages than flat valves, and thus reducing wiredrawing, both for admission and for exhaust. Compared with similar locomotives having flat valves and doing the same work during a lengthy period, these engines with piston-valves have shown an economy of 10 per cent. in coal consumption.

The blast-pipe is generally of the French system with two movable flaps, Fig. 22, Plate 61. In some cases, especially on the Est, a transverse edge, as shown on the drawing, has been added with advantage.

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* The tracings of the details, reproduced on this Fig and on Plates 62 and 63, have been kindly furnished to the author by Mr. A. de Glehn, General Manager of the Société Alsacienne de Constructions Mécaniques.

For oiling the mechanism, the Midi and Est use the cups shown on Fig. 23, Plate 61, where the oil-flow can be regulated at will. This cup is designed for moving parts, such as rod ends. On fixed parts, such as crosshead guides, the opening is at the bottom of the cup, Fig. 24, and a cock is provided to stop the flow whilst standing.

Some railways have substituted compressed air for steam for working the sand-blast; the casting shown by Fig. 25, Plate 61, is provided at the bottom of the sand-box; air comes through the pipe on the left, and divides in two branches; one strikes the sand, and, with the addition of the second branches, carries it down to the rail under the wheels. It will be noticed on Fig. 8, Plate 52, that two sand-boxes are provided, each with pipes for working in both directions. There is a tendency in France to revert to the old system of placing sand-boxes on the top of the boiler, for keeping the sand dry.

IX. *Opinions of French Locomotive Superintendents.*

The locomotive superintendents of some of the large French railway companies have kindly given to the author of the present Paper their opinion on 4-cylinder compound locomotives. These opinions are as follows.

M. Du Bousquet, Locomotive Superintendent of the Northern Railway, says that :—

"The question of compound locomotives was taken up in 1884 by the Chemin de fer du Nord: in that year a 4-cylinder compound locomotive was ordered from the Société Alsacienne de Constructions Mécaniques: the boiler was the same as on the ordinary express locomotives of the company, the working pressure was the same, namely 11 kg per cm^2 (156·55 lbs. per square inch), the diameter of the cylinders of the ordinary locomotive, 460 mm (18$\frac{1}{8}$ inches), was preserved for the low-pressure cylinders of the compound. In fact, the only essential difference was that, in the compound, the steam passed at first through cylinders of 330 mm (13 inches) diameter.

"During a period of nearly eighteen years, from 1884 to 1902, the coal-consumption of this 4-cylinder compound, compared with ordinary locomotives, has been constantly less, the average consumption being 8·6 kg per km (30·5 lbs. per mile), against 10·4 kg (36·92 lbs. per mile) for the ordinary locomotives, saving 1·8 kg per km (6·39 lbs. per mile).

"The oil consumed was 2·4 kg per 100 km (8·51 lbs. per 100 miles) against an average of 1·9 kg (6·7 lbs.) for the ordinary locomotives. But the extra expense resulting from this increased consumption was very small, owing to the low price of the oil consumed, 28 centimes per kg (1·2 pence per lb.).

"The cost of repairs did not vary much; still they were 2 centimes higher per km (0·3 of a penny per mile) for the compound.

"Would it be possible to obtain this well-proved saving of 1·8 kg per km (6·39 lbs. per mile) with single expansion locomotives fitted with an improved mechanism of steam distribution, such as Corliss valves? I do not believe so, for the saving is mainly due, in my opinion, to the reduced condensation of steam in the cylinders resulting from the compound system.

"The economy of coal for our company, which gets cheap coal on its lines, may appear of secondary importance. But it must be observed, and that is of chief importance, that the economy is obtained only during a fraction of the total run. For instance, an ordinary goods-engine, running down grade with steam shut off, does not consume more than the compound under the same circumstances.

"In fact, the saving is obtained on the level parts and chiefly on rising gradients. The mileage corresponding to the saving is much below the total mileage. This saving for each kilometre of level or rising line is far superior to the average. The result is that, instead of being kept in the tender, the coal so saved may be burned in the fire-box. Under these new conditions the same quantity of steam is generated, but the useful effect obtained is greater; the speed on rising gradients is increased, or the weight hauled is larger, or speed and weight are both increased.

"Important results are thus obtained; the daily mileage of locomotives, drivers, firemen, train staff is greater; carriages and wagons are better utilized; piloting and supplementary trains are dispensed with.

"This is well shown by the following examples.

"The present express compound locomotives haul a train of 200 *t* (196·84 tons) from Paris to Survilliers in 19 minutes, with a rising gradient of 1 in 200 for the greatest part from St. Denis to Survilliers, the speed on this gradient being 100 km an hour (62·13 miles per hour). That is exactly the shortest time that was consumed, and it is still consumed when running down from Survilliers to Paris.

"The average speed of fast trains has been greatly increased by the mere augmentation of speed on level and rising gradients without exceeding the limit of 120 km an hour (74·5 miles per hour) attained on falling gradients for a long time.

"The reduction in the duration of journey allows runs of 300 km (186·4 miles) with one engine and one crew, although the weight of passenger trains attains and frequently exceeds 300 *t* (295·26 tons).

"The results obtained with 4-cylinder compounds and 6-coupled wheels of 1·750 m (5 feet $8\frac{7}{8}$ inches) diameter, working goods trains, are not less satisfactory. Coal trains weighing 925 *t* (910·3 tons), of which 600 *t* (590 tons) useful weight, make in 7 hours the run from Lens to Paris, *viâ* Ormoy, 230 km (143 miles), with one engine, one crew and one train staff. With the old 8-coupled wheels of 1·300 m (4 feet $3\frac{3}{16}$ inches) diameter, the weight hauled was 675 *t* (664 tons)—of which 400 *t* ($393\frac{1}{2}$ tons) was useful weight—and the time was 14 hours for the same distance.

"The saving in engines, drivers, firemen, conductors, brakemen, the increased tonnage, the better utilization of wagons, are such that the common objections against the compound locomotives, namely complication of parts, increased risk of breakdown, increased expenses of up-keep, appear as of no value.

"However, owing to the greatly increased pressure of steam, special attention must be paid to the boilers. Copper does not stand well the high temperatures resulting from increased pressures. With the use of manganese bronze the breaking of stays has completely ceased, but we have no satisfactory material for tube plates.

"We had no trouble with the flanges of the front plate of the outside fire box, so long as they were made of wrought iron, but frequent inconvenience results from the use of mild steel. We return to the use of iron plates, at least for the present."

M. Baudry, Locomotive Superintendent of the P.L.M. Railway, made a communication to the Société des Ingénieurs Civils, on 7th October 1898, of which the conclusion is as follows*:—

"Some people may be of opinion that the importance of the coal saving due to compound locomotives is small, and even vanishes when the price of coal is very low. That is a mistake, as the saving of coal means really an increased power of the locomotive. In fact there is no saving of coal for a certain work performed, but there is more work for the same coal-consumption; thence result other important savings, namely less locomotives, less drivers, less firemen, and less trains are necessary for a given traffic. These aggregate savings, which do not depend upon the price of coal, greatly exceed, in the majority of cases, the saving of coal proper. If the weight of trains is not increased, then an acceleration in speed is possible, and in that way the construction of more economical locomotives has resulted, during the last few years, in an increase of speed on all French lines."

M. Moffre, Locomotive Superintendent of the Southern Railway, declares that he considers compound locomotives as undoubtedly advantageous; the results in service prove that, if expenses for repairs and for lubrication are a little larger with these engines than with single-expansion locomotives worked in comparison, they haul with a slightly less coal-consumption much heavier trains (by about 40 per cent.).

M. Salomon, Locomotive Superintendent of the Eastern Railway, writes that:—

"Compared with the ordinary locomotive, the compound locomotive has the important advantage of a coal economy, which varies with the nature of the service, but which is, on an average, from 10 to 15 per cent. With the use of four cylinders the symmetry of the engine is preserved, inertia forces are in better equilibrium, the turning force is more uniform, the total work is divided between two axles, and stresses are more evenly distributed on the frame. As a consequence, the mileage between two heavy repairs in the shops has been increased by 50 per cent.

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* Consulted by the author of the present Paper, M. Baudry referred to that communication as still expressing his actual opinion.

"In my opinion, the use of these locomotives marks an important improvement, which has not been accompanied by any trouble in service; the only objections which have been often made to the use of compound locomotives are want of elasticity in their power, and excessive compression of steam at high speed. As regards the first objection, the use of independent gears for the high and for the low-pressure cylinders allows a satisfactory distribution of steam under very different rates of weight and speed. The second objection vanishes with large clearances and sufficient area of steam passages on the low-pressure cylinders. In this respect piston-valves will be quite suitable if they remain sufficiently tight."

Conclusions.

From a lengthy experience with more than a thousand engines, and from the unanimity of opinion of all having experience of these engines, it may be taken for granted that the four-cylinder compound system possesses marked advantages, at least under the conditions of service prevailing on main French lines. Thanks to their use, French railways have been enabled to increase largely the weight and the speed of their trains, for goods as well as for passenger service, without any large increase of coal-consumption per kilomètre run. In fact, it is rather under-estimating the merits of the compounds to say that by their use the weight of trains is increased by one-third with the same cost of fuel over what it was with the best simple engines used before; or, if not the weight, speed is increased, and in many cases both weight and speed.

In other words, the compounds would take a traffic equal to four, against a traffic equal to three, the number of engines and the cost of fuel and wages remaining the same. The initial cost of the compounds is higher, the expenses for repairs may be somewhat greater, but the increase of traffic is such that the economy is obvious. As regards the cost of repairs, there is still some doubt as to their exact amount, as a very large proportion of the compounds have been running for a few years only; but it must be remarked that the increase of expenses will very likely be due to the boilers working at a high pressure, and it seems that the same pressures would be necessary for simple engines, if they were to compete with compounds.

To this must be added, specially for passenger service, the advantages of greater speed, of more punctuality, and of dispensing in many cases with pilot engines or with supplementary trains. From a mere practical point of view the French administrations feel satisfied with the great extension they gave to the four-cylinder compound system, from which resulted economy as well as a large improvement in their services.

A complete solution of the problem would require a proof that the same results might not be obtained in some other way. Available data are not sufficient to give such a proof in an indisputable manner; still, it seems difficult to build an ordinary locomotive quite equal in every respect to the latest compounds.

It is clear that simple two-cylinder engines might be made with the same large boiler and work with the same high pressure, but it is nearly as clear that, with the ordinary valve-gear of the locomotive, steam at such a high pressure cannot be as well utilized as by compounding; there is little doubt that the simple locomotive would require more steam for the same work or give less work for the same quantity of steam. In addition there is a real difficulty in making all the parts of the simple engine strong enough to stand without undue wear the great stresses resulting from the increased pressure on large pistons, although this difficulty may be overcome.

Another plan would be to improve the steam distribution of the simple engine by the use of systems such as Durant and Lencauchez's or Bonnefond's, which have been tried to some extent in France. In these systems separate valves are provided for admission and for exhaust on both sides of the cylinder. Although these systems have been used for several years on a few locomotives, and seem to have produced a certain economy in fuel, they remain as yet exceptions, and cannot be considered as a practical solution of the locomotive problem. For locomotives, as for marine engines, it is difficult to find a substitute for the simple slide-valve, flat or piston.

According to some German engineers, superheating steam would be equal to compounding. Theory proves that the effect of superheating may be very good, and the results of experiments appear satisfactory. It is hardly necessary to recall here the very interesting trials of Mr. J. A. F. Aspinall in that direction. All locomotive engineers will watch with great interest the progress of that system, but as yet it may be considered as being in an experimental stage. It must be remarked that superheating does not seem to exclude compounding.

Until the question is solved, practical men in France will probably keep to the system of four-cylinder compounds, the merits of which are firmly established. This of course does not exclude experiments of other systems, and no one today can boast that he has made an engine which will long remain without a rival.

Compound locomotives, like any other engines, must be used under proper conditions of service to be economical. Powerful locomotives must have sufficiently heavy weights to haul, or else they become wasteful. It would be a mistake to start them on branch lines with light trains. But in practice a railway company is never deficient of old locomotives, which are quite fit for this restricted traffic.

An opinion, which seems to prevail, is that compound locomotives may be economical during long runs, but that their advantage is lost when they stop and start frequently, owing to the direct admission of steam to the low-pressure cylinders at starting. This opinion is rather too dogmatic, and the question requires some consideration. In many cases, with four-cylinder compounds the tractive power necessary for starting from rest is obtained without this direct admission, or steam is admitted in that way only for the very first revolution of wheels. The engine is then worked compound, but in full gear for all cylinders. Of course steam is not so well utilized as with a proper degree of expansion in each cylinder, but, even in that case, the compound compares favourably with a simple locomotive working in full gear.

Let us suppose a compound with two cylinders of 340 mm (13⅜ inches) and two cylinders of 530 mm (20⅞ inches) diameter, the stroke being 640 mm (25¼ inches), and the effective pressure in the boiler 15 kg per cm^2 (213 lbs. per square inch), and a simple engine with cylinders of 480 (19 inches) × 640 mm (25¼ inches), working under an effective pressure of 12 kg per cm^2 (170·6 lbs. per square inch). This represents fairly what might be considered as equivalent in practice. The diameter of wheels is the same in both cases. With a full admission of steam, i.e. rectangular diagrams, the work of steam on the pistons during a revolution would be, in kilogrammètres, $4 \times \frac{48^2}{1 \cdot 273} \times 0 \cdot 64 \times 12$, for the simple engine; this reduced to 85 per cent., on account of drop of pressure and rounded corners of diagrams, would be 44,500 kilogrammètres (321,868 foot-pounds).

With the compound, working full gear, the effective pressure would be 5·5 kg per cm^2 (78·2 lbs. per square inch) in the receiver, and the work exerted on the pistons, during one revolution, would be

$$4 \times \frac{34^2}{1 \cdot 273} \times 0 \cdot 64 \times 9 \cdot 5 + 4 \times \frac{53^2}{1 \cdot 273} \times 0 \cdot 64 \times 5 \cdot 5,$$

and, after a reduction to 80 per cent. (the drop of pressure being somewhat larger in the compound, 42,000 kilogrammètres (303,786 foot-pounds), or nearly the same value.

The capacity of the high-pressure cylinder of the compound being one-half of the capacity of the cylinder of the simple engine ($48^2 = 2 \times 34^2$), the volume of steam consumed is one-half in the compound, but at a greater density. The weights are as 0·6 in the compound to 1 in the simple engine. This proportion is altered by the condensation of steam on the cylinder walls, but this would be rather in favour of the compound.

This approximate calculation, not far from the conditions of practice, shows that without direct admission of steam to the low-pressure cylinders, the compound may be nearly equal to the simple locomotive as regards maximum tractive power, but with an important economy in steam when full gear working is considered.

The Paper is illustrated by Plates 50 to 64 and 2 Figs. in letterpress.

Discussion on 18th March 1904.

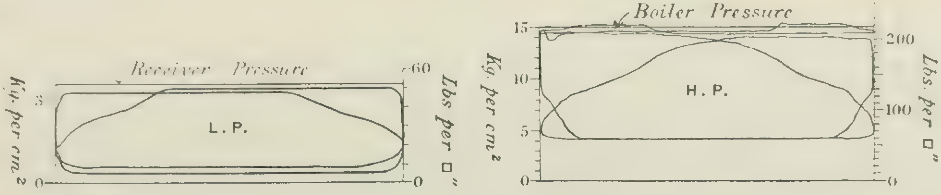
M. SAUVAGE said he had little to add to the Paper which had been read, and wished to apologise for its great length. The French four-cylinder compounds, from the point of view of French locomotive engineers, had proved very efficient, and efficiency was the quality which was required for hard railway service. The building of the compounds in France might be divided into two phases. In the first, the locomotives had been made more powerful than the ordinary locomotives which were used before, but the difference was not so very large. But within a few years it has been found that even the increased power of the compound locomotives was not sufficient, and that it was necessary to take advantage of the system to the fullest extent. The building of very powerful locomotives then resulted, which might be divided into three different classes: first, for express service, heavy passenger and very fast trains, the "Atlantic" type of engine. He doubted whether any more ordinary express compounds of the old style, with a bogie and only 2-coupled wheels, would be built; the Atlantic type was more powerful and seemed to replace that locomotive. The 3-coupled locomotive with the bogie in front was also largely used, and was fit for ordinary passenger traffic and for goods traffic. By its use the speed of many goods trains had been largely increased in France, and, at the same time, the weight was larger than before.

Dealing with the heavy mineral traffic, it was found that the old 4-coupled locomotive, which had been a little left out for some years, would still be useful if built with more power, that is, with four cylinders working compound; and in addition to the 4-coupled axles it had been found useful to put the pony truck in front. Thus, the more modern locomotives on the French railways might be divided into three classes—the Atlantic type, the 3-coupled locomotive, and the 4-coupled locomotive. All these had a very large boiler, and in some cases the same boiler was used for the three different classes of locomotive. The grate area was over 30 square feet, nearly 34 in some of the engines, and the heating surface some 3,500 square feet.

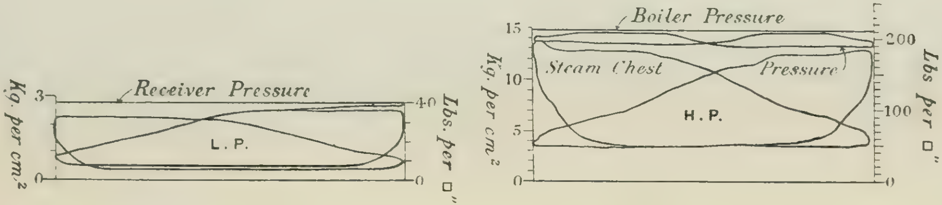
He had just received some very interesting results from the engineer of the Paris-Orléans Railway, which had recently put into service some of these new compounds. The results were shown on Figs. 38 and 39 (pages 382–385); in one case a train, weighing 350 tons, exclusive of the locomotive and tender, had been taken over nearly 200 miles at an average speed of 50 miles an hour, and during one part of the trip, over a length of 73 miles, the average speed from end to end was 63 miles an hour. Indicator diagrams had been taken and the effective tractive-power measured. It measured, on an average, 1,200 H.P., and in some places 1,800 H.P. The 1,800 H.P. was not the indicated power, but the calculated tractive power of the locomotive as exerted by the wheels on the rails, and it was a very high figure indeed. In one of the more remarkable instances, one point worthy of remark was that the water-consumption was particularly low, indicating that the steam-engine in itself was very good. In all the experimental trials the water-consumption was as low on the average for a number of trials as only 24 lbs. of water per H.P. per hour. One lb. of coal was sufficient for 7·7 lbs. of water; and he wished to call particular attention to the fact that the consumption of water was so low. Some very fine indicator diagrams taken on the engines were shown in Figs. 38 and 39 (pages 382–385). To develop such a high power, it was necessary that the steam consumption per I.H.P. must be very small, which was proved by the results. Everybody who had had experience with the

Fig. 38. *Paris-Orléans Railway.* *Engine No.* 3001. *Trial* 115, 20 *Nov.* 1903.

Train B. Nominal Speed, 55·9 m.p.h. Tonnage hauled, 346 tons from Paris-Ivry to St. Pièrre des Corps.
Safety-valve fixed at 213·3 lbs. per sq. in. (Variable exhaust openings.)

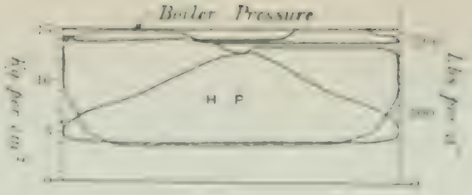


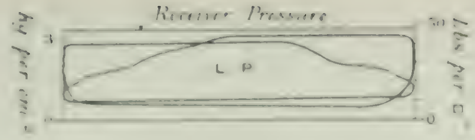
	H.P.	L.P.
Speed m.p.h. . .	36·6	
Regulator open .	90%	
Pressure, lbs. per sq. in.	213·3	54
Admission . . .	65%	70%
Horse-power . .	723·9	631·2
Total H.P	1355·1	



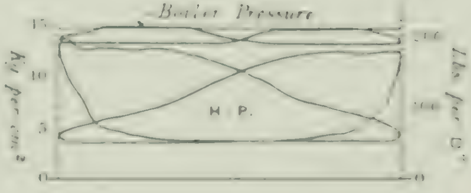
	H.P.	L.P.
Speed m.p.h. . .	63·4	
Regulator open .	60%	
Pressure. lbs. per sq. in.	210·4	39·8
Admission . . .	50%	65%
Horse-power . .	913·3	608·5
Total H.P.	1521·8	

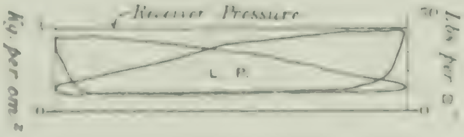
	H.P.	L.P.
Speed in m.p.h.	[illegible]	
Regulator open	[illegible]	
Pressure, lbs. per sq. in.	[illegible]	[illegible]
Admission	[illegible]	[illegible]
Horse-power	[illegible]	[illegible]
Total H.P.	[illegible]	



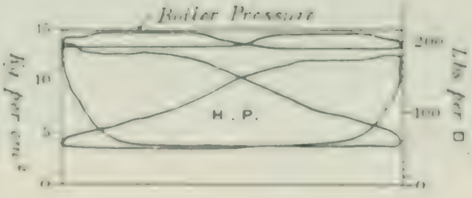


	H.P.	L.P.
Speed in m.p.h.	[illegible]	
Regulator open	[illegible]	
Pressure, lbs. per sq. in.	[illegible]	[illegible]
Admission	[illegible]	[illegible]
Horse-power	[illegible]	[illegible]
Total H.P.	[illegible]	





	H.P.	L.P.
Speed in m.p.h.	[illegible]	
Regulator open	[illegible]	
Pressure, lbs. per sq. in.	[illegible]	[illegible]
Admission	[illegible]	[illegible]
Horse-power	[illegible]	[illegible]
Total H.P.	[illegible]	



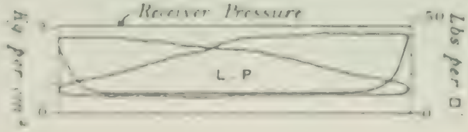
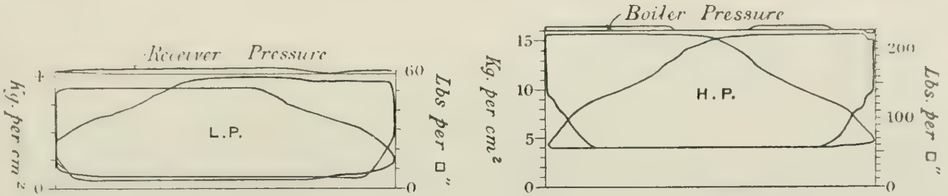
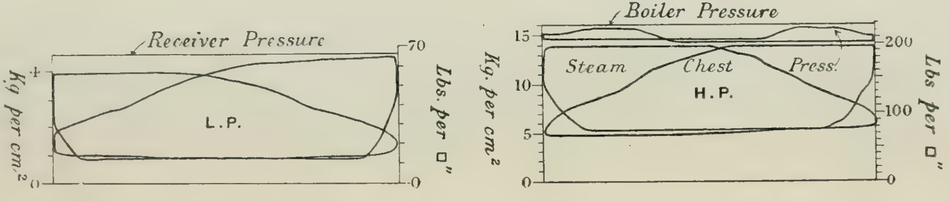


Fig. 39. *Paris-Orléans Railway.* *Engine No.* 3001. *Trial* 121, 27 *Nov.* 1903.

Train A. Nominal Speed, 59 m.p.h. Tonnage hauled, 250 tons from Paris-Ivry to St. Pièrre des Corps. Safety-valve fixed at 227·5 lbs. per sq. inch. (Variable exhaust openings.)

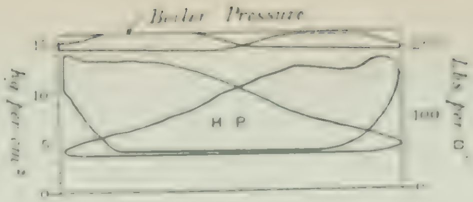


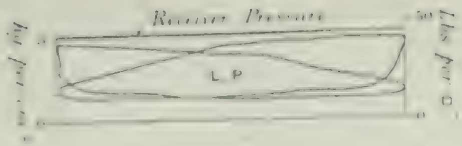
	H.P.	L.P.
Speed m.p.h. . .	27·3	
Regulator open .	76%	
Pressure, lbs. per sq. in.	227·5	58·3
Admission . . .	60%	65%
Horse-power . .	559·2	521·7
Total H.P.	1080·9	



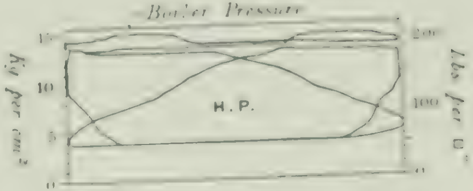
	H.P.	L.P.
Speed m.p.h. . .	48·4	
Regulator open .	48%	
Pressure, lbs. per sq. in.	227·5	65·4
Admission . . .	62%	65%
Horse-power . .	770·3	834·4
Total H.P.	1604·7	

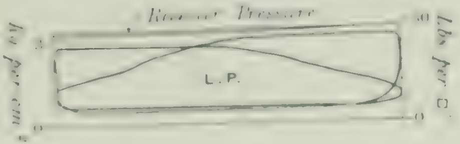
	H.P.	L.P.
Speed m.p.h.	[illegible]	
Regulator open	[illegible]	
Pressure lbs. per sq. in.	[illegible]	[illegible]
Admission	[illegible]	[illegible]
Horse-power	[illegible]	[illegible]
Total H.P.	[illegible]	



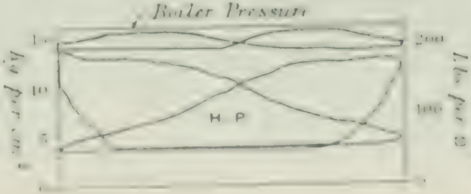


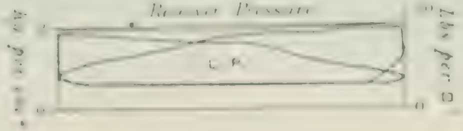
	H.P.	L.P.
Speed m.p.h.	[illegible]	
Regulator open	[illegible]	
Pressure lbs. per sq. in.	[illegible]	[illegible]
Admission	[illegible]	[illegible]
Horse-power	[illegible]	[illegible]
Total H.P.	[illegible]	





	H.P.	L.P.
Speed m.p.h.	[illegible]	
Regulator open	[illegible]	
Pressure lbs. per sq. in.	[illegible]	[illegible]
Admission	[illegible]	[illegible]
Horse-power	[illegible]	[illegible]
Total H.P.	[illegible]	





compound locomotive in France—and the experience began now to be a long one—was entirely satisfied with their working, and thought that the four-cylinder compound was an efficient, handy, and also economical engine.

The PRESIDENT rose to protect the author from being overwhelmed by compliments and thanks from every subsequent speaker. He accorded M. Sauvage the Institution's thanks at the beginning of the discussion in order that he might, on behalf of all the members, convey to the author their appreciation of what he had done for them, and in order that subsequent speakers might go straight to the point in a perfectly business-like way, knowing that they were speaking to an expert who knew what he had said, and was not afraid of any amount of discussion.

M. Sauvage had presented a very big Paper, not long from the strings of words that were put into it, but big from the Tables, the diagrams, and the beautiful mechanical drawings of details. He might remind the author that the Institution was founded in 1847 by George Stephenson, and that the Institution was pre-eminently typified by the locomotive engine, which was the type of machinery and engineering construction put into motion, engineering construction that had life given to it, as contra-distinguished from statical engineering, which was construction that was not capable of movement. It was, therefore, an extremely welcome subject to the Institution, and he was sure the author, if he looked at the number of the audience, would receive a sufficient compliment for the trouble he had taken in coming over from France to give the Paper. It would be noticed on page 333 that the author mentioned that "The new Atlantic type recently built for the Paris-Orléans Railway by the Société Alsacienne de Constructions Mécaniques, Fig. 5, Plate 51, is of special interest as being the most powerful express locomotive as yet made for the French lines." The Institution had the advantage of Mr. de Glehn's presence, who was the engineer of that company of locomotive builders, and he asked him to favour the members by opening the discussion.

Mr. ALFRED G. DE GLEHN (of the Société Alsacienne de Constructions Mécaniques) said that as an Englishman separated by more than thirty years' residence on the Continent from what he might say was the original home of mechanical engineering, he felt it a quite peculiar pleasure to be able to assist for once at one of the Institution's meetings, and considered it a great honour to be asked to say something about the four-cylinder engine. Unfortunately, M. Sauvage had said really almost all there was to be said, and he was afraid that in what he would wish to say he would be repeating a great deal of what had been already said. The author mentioned the fact that there were 1,577 compound engines at present running in France, the greater number being four-cylinder ones. Since that time more than 90 new engines had been put into service. In addition, on the Continent outside of France there were more than 600 four-cylinder engines running at present, which gave a total of more than 2,000 of such engines working on the Continent at the present time. In England and on the Continent engineers had been doing their best to increase the power of engines, without increasing at the same rate their weight, but he thought that American practice had been different. The Americans had increased their power, but they had also enormously increased their weight. Already signs of a change could be seen, or rather a wish for a change. American engineers were beginning to see that very heavy engines had great drawbacks, and attempts had been made to get more power, by what the author called a more efficient engine principally by using the steam better; and there was no doubt that would lead to a very great and rapid change in American practice. It was always very dangerous to prophesy, but he was perfectly confident that it would be a change more in the direction of what was being done in England and on the Continent than that they should go in the direction the Americans had been following.

In the following remarks he would confine himself to the type which was called by the somewhat cumbersome title of four-cylinder divided and balanced compound. It had also often been called the de Glehn system, but he wished to state plainly that that was not correct; for though he had done something towards the

(Mr. Alfred G. de Glehn.)

evolution of the type, others, and particularly the Northern of France engineers, had done as much, if not more, than he had, and without them the engine would never have been brought to its present state of perfection. The engine had been criticised principally as being a complicated engine. There was no doubt it was so, but was it not true that almost all progress in mechanics had been by complication? It was quite useless to multiply instances; but they had only to think of the automatic air-brake, which certainly was not simple, but very complicated, and yet everybody was very glad to have it.

The question that must be asked in introducing any complication was—Was the complication justified? That was at the bottom of every question connected with the compound engine. Its origin was as follows: The engines that were used on the Northern of France Railway were powerful express engines with crank-axles, which were constantly breaking. The Northern of France wished to have a stable engine, as stable as an inside-cylinder engine usually was, and did not want to have those constant breakages. How to manage that was the question. The proposal he made was to divide the engine into two, and to make an inside-cylinder and an outside-cylinder engine. There was room for that, and it was thought that by that means the breakage of the crank-axles would be prevented, and that had been the fact. Another most important thing was the question of the balancing. It was, of course, even with very powerful engines, comparatively easy, especially when large wheel diameters were used, to balance properly the revolving weights; where the difficulty came in was with the reciprocating parts. Those had to be balanced by revolving weights, which entailed successive increase and decrease of pressure on the rails. With very powerful engines at great speeds those variations might become dangerous, and must be kept within pretty definite limits. The question was getting so serious that in Germany it had become the rule to specify a certain percentage of increase or decrease, otherwise the balancing of the reciprocating parts must be reduced. With a too great reduction in the balancing of the reciprocating parts, there was a risk of a very perceptible fore-and-aft motion of the engine; the balancing was not sufficient. But in the four-cylinder compound, with two inside and two outside cylinders, the weights of the reciprocating parts were so arranged that they practically balanced one another, thus being able to dispense with revolving weights to balance the reciprocating parts, the balancing of the revolving parts then being easily dealt with. That was, he thought, an important point, and became more important with the increasing power required in engines, the wheel diameters remaining about the same as before. This improved state of things was useful in another way, for the steadiness of the pressure on the rails meant less slip. There were even reasons for thinking that in ordinary engines there was a frequent, if not continuous, small slipping, the number of revolutions not always corresponding to the distance traversed. As at the same time the four-cylinder acted upon four cranks at 90°, much more uniform turning moment was obtained, thus approaching the motor drive of electric locomotives or cars.

Referring to the division of the total work over an increased number of parts, there was, in fact, an inside-cylinder engine and an outside-cylinder engine each doing half the work. For each there was as much room as there was in an outside or inside-cylinder engine having all the work to do, and for each half could be given the same length of bearings as for the simple engine, reducing the diameters proportionately.

With regard to the valve-gear, there was the same division, and it was the utility of that arrangement which had been the most questioned. If one had a valve that was tight, and would keep really tight, and would with ordinary care remain balanced, that was collapsible or would lift so as to do away with the need for relief valves, and, lastly, that would let the steam in and out of the cylinder as freely and with as little change of section and direction as an ordinary D valve, then perhaps the only justification of the four gears and two reversing-shafts would be the possibility it afforded of adjusting the relative cut-offs in the high- and low-pressure cylinders with a great degree of nicety to the varying running conditions. That was no small advantage, for it was extraordinary how sensitive a four cylinder engine was in that respect.

(Mr. Alfred G. de Glehn.)

TABLE 20 (*continued on opposite page*).

Leading Dimensions of various types of Compound Locomotives in France.

(Mr. de Glehn's remarks.)

			Nord. American Type. 1898.	Nord. Atlantic Type. 1901.
1	Weight of engine (empty)	tons	47·1	60
2	Water in boiler and fuel on the grate .	tons	4·4	5
3	Weight of engine in running order . .	tons	51·6	65
4	Weight on coupled wheels . . .	tons	31·9	32
5	Weight on trailing wheels . . .	tons	—	14¼
6	Weight on bogie	tons	19·7	18¾
7	Mean diameter of boiler shell . .	ft. ins.	4 5⅛	4 $9\frac{5}{16}$
8	Working pressure	lbs.	213	228
9	Number of tubes (Serve's ribbed pattern) . .		105	126
10	Length of tubes between tube plates .	ft. ins.	12 $9\frac{9}{16}$	14 $1\frac{5}{16}$
11	Internal diameter of tubes	ins.	$2\frac{9}{16}$	$2\frac{9}{16}$
12	Internal heating surface of tubes . .	sq. ft.	1768·8	2158
13	Internal heating surface of fire-box .	sq. ft.	127·2	167
14	Internal heating surface total . . .	sq. ft.	1896	2325
15	Area of grate	sq. ft.	25·6	29·5
16	Diameter of H.P. cylinders . . .	ins.	13⅜	13⅜
17	Diameter of L.P. cylinders . . .	ins.	21¼	$22\frac{1}{16}$
18	Stroke of pistons	ins.	$25\frac{3}{16}$	$25\frac{3}{16}$
19	Diameter of driving wheels . .	ft. ins.	6 11⅞	6 8½
20	Diameter of trailing wheels . . .	ft. ins.	—	4 7⅞
21	Diameter of bogie wheels	ft. ins.	3 5	2 11⅞
22	Total wheel-base of engine . . .	ft. ins.	24 0⅜	27 10⅝
23	Total length of engine	ft. ins.	32 5½	37 8⅛
24	Total width of engine	ft. ins.	9 7⅞	9 6⅜
25	Gauge	ft. ins.	4 8½	4 8½

(concluded from opposite page) TABLE 29.

Leading Dimensions of various types of Compound Locomotives in France.

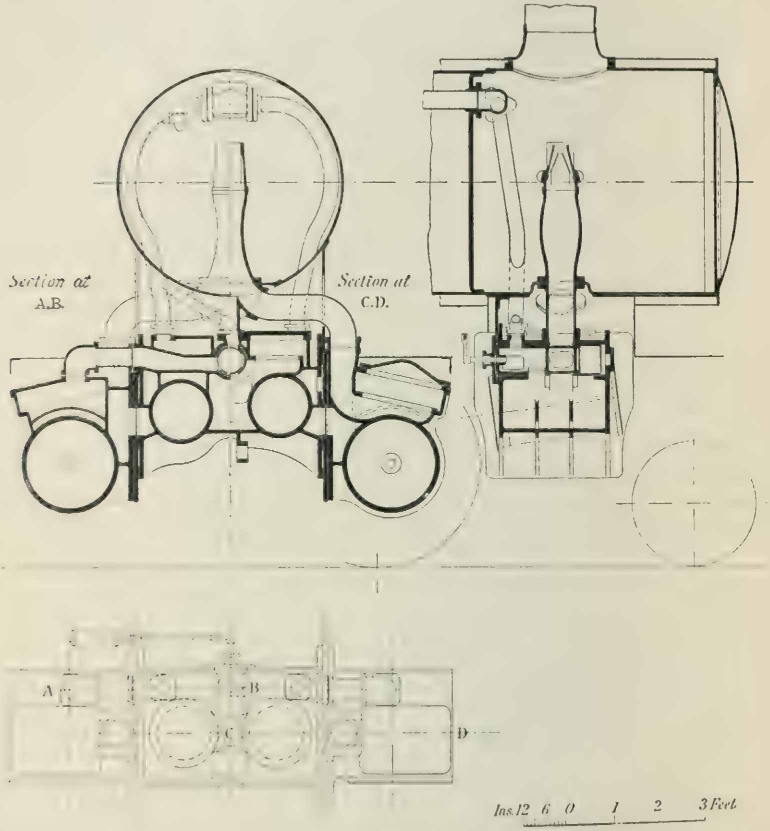
(Mr. de Glehn's remarks.)

P.O.	Nord.	A.L.	P.O.	Midi.	Centre.	P.O.	
Atlantic Type.	10-wheel.	10-wheel.	10-wheel.	Consolidation Type.	12-wheel.	Consolidation Type.	
1903	1897	1901	1903	1901.	1904	1904.	
65·5	55·5	61·8	66	67·5	63·8	67·2	1
6·4	4·7	6·2	6·4	6·1	6·1	6·4	2
72·4	58	67·9	72·9	70·7	78·7	73·6	3
35·4	42·5	47·2	51·4	63·5	62·9	66·2	4
14·5	—	—	—	—	—	—	5
21·5	15·7	20·7	21·5	7·2	15·8	7·4	6
5 5½	4 6¾	4 9¾	5 5¾	5 1	4 8¾	5 5½	7
228	213	228	228	215	213	213	8
139	107	125	139	148	126	139	9
14 5¼	13 5 5/16	15 10	14 5¼	14 1 1/16	13 5 5/16	14 5¼	10
2 3/16	2 3/16	2 3/16	2 3/16	2 3/16	2 3/16	2 3/16	11
2402·9	1893·4	2091	2402·9	2534·5	2035·4	2402·9	12
174·1	130	159	174·1	170·8	153·5	174·1	13
2577	2023·4	2250	2577	2075·3	2188·9	2577	14
33·4	26	29·5	33·4	29·8	24·4	33·4	15
14 3/16	13⅝	14¾	14 3/16	15 3/16	14 3/16	16 3/16	16
25¾	21⅝	22 5/16	23⅜	23⅜	22 5/16	23⅜	17
25 3/16	25 3/16	25 3/16	25 3/16	25⅝	25⅝	24⅝	18
6 8½	5 9	6 0¾	6 0¾	4 7½	4 8¾	5 1	19
5 0¾	—	—	—		—	—	20
3 1⅞	2 9¾	2 11½	3 1⅝	2 9½	2 7½	2 9¾	21
28 6½	24 9¾	26 5	27 0¾	23 1¾	27 8¾	24 1¾	22
38 8¾	34 0¾	37 8¾	38 2½	36 10½	41 0½	38 0¾	23
9 9⅞	9 7¼	9 10¾	9 9¾	9 10½	9 10½	9 11	24
4 8½	4 8½	4 8½	4 8½	4 8½	4 8½	4 8½	25

FIG. 40.

General arrangement of Cylinders and Starting Valve.

Eight-coupled 10-wheeled Locomotive Eastern and Southern of France Railway.



To work to the best advantage, running up a bank, the best adjustment would be—say a cut-off of 55 per cent. in the high and 65 per cent. in the low-pressure cylinders; running down the bank or on the level they should notch back to 45 per cent. in the high- and 65 per cent. in the low-pressure cylinders as before. As, however, in spite of its defects, he still thought that the D valve was, in many respects, the best valve they had at present for locomotives, the difficulty of moving and lubricating them in engines with a high pressure was much reduced in the four-cylinder compounds, as the high-pressure valves were, of course, partially relieved by the receiver pressure. With the low-pressure valves of course there was no difficulty. In some very recent and very powerful continental four-cylinder engines, when all four valves—two piston-valves for the high-pressure cylinders and two D valves for the low, all driven by two links—were used, there had been very considerable trouble with the links and motion work. He need hardly say anything as to the rapid starting possible with these engines, that being due to the four cranks and the intercepting valve, which allowed the high-pressure cylinders to exhaust direct to the chimney, while live steam at reduced pressure was admitted to the low-pressure cylinder.

Easy and rapid starting were becoming of extreme importance for suburban traffic. He had just built some new engines for one of the circular lines round Paris, eight-coupled engines, with a bogie and four cylinders, in which the starting was extremely remarkable. The Eastern of France Railway had been making some experiments by working suburban traffic alternately with an ordinary engine with six-coupled wheels and 48 tons adhesive weight, and, after the times had been noted on those trains, with one of the six-coupled four-cylinder engines which the author had described, with exactly the same adhesive weights. On a journey of 50 or 60 minutes, some 10 minutes had been gained by the increased rapidity of starting of the four-cylinder compound.

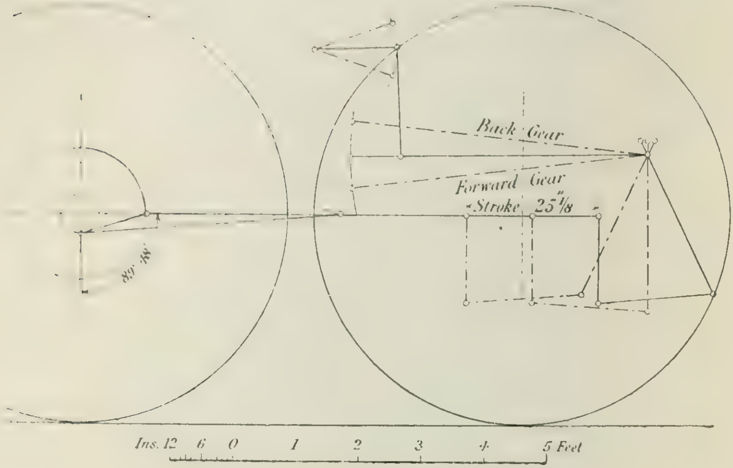
The author had alluded already to the last point he (Mr. de Glehn) wished to insist upon, namely, that for high-speed engines great importance had to be attached to the arrangement of the steam

(*Continued on page 398.*)

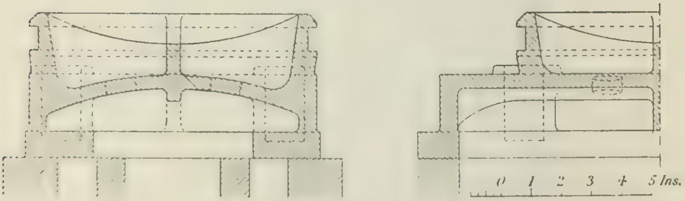
"Atlantic" and six-coupled ten-wheeled Locomotives for the Paris-Orléans Railway.

Steam Distribution, H.P. Cylinders.

FIG. 41.



High-Pressure Slide-Valve.



Stroke of piston	25·2 ins.
Throw of Eccentric	7·47 ins.
Keying Angle	89°
Outside-lap	1·06 ins.
Negative inside lap	0·12 ins.

TABLE 21.

Steam Distribution, High-pressure Cylinders.

Gear.		Lead. Inch.		Maximum opening Inch.		Admission. Per cent.		Expansion Per cent.		Pre-release Per cent.		Release Per cent.		Compression Per cent.		Pre-admission Per cent.	
		F.	B.	F.	B.	F.	B.	F.	B.	F.	B.	F.	B.	F.	B.	F.	B.
Maximum	F	0·3	0·3	1·79	1·61	79·5	81	12	11·5	8·5	7·5	93·5	93·75	6·25	5·75	0·25	0·5
	B	0·3	0·3	1·82	1·51	80	80·5	11·5	12	8·5	7·5	94·5	94	5·25	5·5	0·25	0·5
60 per cent.	F	0·3	0·3	0·91	0·85	60	60	22·5	23	17·5	17	87·5	87	12·5	11·75	1·0	1·25
	B	0·3	0·3	0·89	0·77	60·5	59·75	22·5	23·25	17	17	87·5	87·5	11·5	11	1·0	1·5
50 per cent	F	0·3	0·3	0·7	0·63	50·5	49·5	26·5	28·5	23	22	84	82	14·5	16·25	1·5	1·75
	B	0·3	0·3	0·68	0·6	51	49	27	29	22	22	84	83	14·25	15·25	1·75	1·75
40 per cent	F	0·3	0·3	0·53	0·49	40	39·5	31	32·5	29	28	79	78	19	19·5	2·0	2·5
	B	0·3	0·3	0·53	0·48	40	39·5	33	33·5	27	27	79	79	19	18·5	2·0	2·5
30 per cent.	F	0·3	0·3	0·41	0·39	30	29	36	35	35	36	72	71	24·5	25	3·5	4·0
	B	0·3	0·3	0·41	0·39	31	31	35	35·5	34	33·5	75	74	22	22·5	3·0	3·5
Mid gear.	F	0·3	0·3	0·3	0·3	11	11·5	34	33·5	55	55	54	55	34	33	12·0	12·0
	B	0·3	0·3	0·3	0·3	12	12·5	34	33·5	54	54	55	55	34	34	11·0	11·0

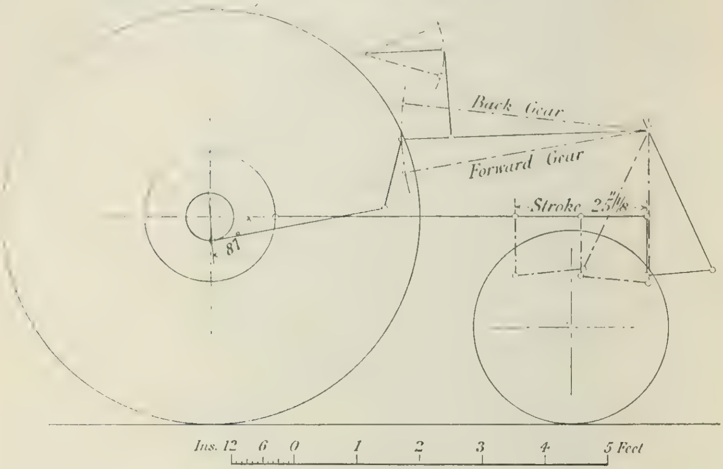
NOTE.—F. Forward. B. Backward.

(Mr. Alfred G. de Glehn.)

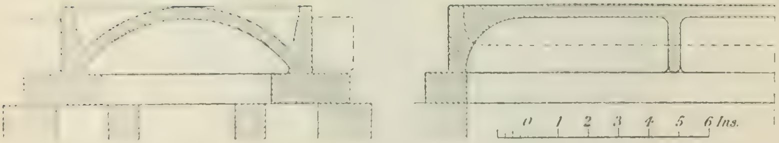
"Atlantic" and six-coupled ten-wheeled Locomotives for the Paris-Orléans Railway.

Steam Distribution, L.P. Cylinders.

Fig. 42.



Low-Pressure Slide-Valve.



Stroke of piston	25·2 ins.
Throw of Eccentric . .	9·05 ins.
Keying Angle	87°
Outside lap	1·06 ins.
Negative inside lap	0·2 ins.

TABLE 22.

Steam Distribution, Low-pressure Cylinders.

Gear.		Lead Inch.		Maximum opening Inch.		Admission Per cent.		Expansion Per cent.		Pre-release. Per cent.		Release Per cent.		Compression Per cent.		Pre-admission. Per cent.	
		F.	B.	F	B	F	B.	F	B	F.	B.	F	B	F	B	F	B
Maximum	F	0·28	0·29	1·77	1·65	80	80·5	11	12·5	9	7	95·5	95	4	4·25	0·5	0·75
	B	0·28	0·29	1·85	1·5	80	80·5	11·5	12	8·5	8	95·5	95	4	4·5	0·5	0·5
60 per cent	F	0·28	0·29	0·93	0·85	61	60	20	21·5	19	18·5	89	88	11·25	11	0·75	1·0
	B	0·28	0·29	0·83	0·75	61	59·5	20	20	19	21·5	89	88	11·25	11	0·75	1·0
50 per cent	F	0·28	0·29	0·69	0·63	51	49	25·5	27	23·25	24	85	84	14	14·5	1·0	1·5
	B	0·28	0·29	0·61	0·59	51	49	25·5	27	23·5	24	85	84	14	14·5	1·0	1·5
40 per cent	F	0·28	0·29	0·53	0·51	42	39	28	31	30	30	81	80·5	17·5	17	1·5	2·5
	B	0·28	0·29	0·49	0·47	41	39·5	30	30·5	29	30	81·5	81	16·75	16·5	1·75	2·5
30 per cent	F	0·28	0·29	0·41	0·39	31	30	33	32	36	38	76	75	21·5	21·25	2·5	3·75
	B	0·28	0·29	0·37	0·39	31	30	34	33	35	37	76	76·5	21·5	20	2·5	3·5
Mid gear	F	0·28	0·29	0·28	0·29	11	12·5	33·5	29·5	55·5	58	57	59	34	30	9·0	11·0
	B	0·28	0·29	0·28	0·29	9·5	11	34·5	30·5	56	58·5	57	58	33	31	10·0	11·0

NOTE.—F. Forward. B. Backward.

(Mr. Alfred G. de Glehn.)

and exhaust pipes and their dimensions, in order that the steam might pass from the regulator to the high-pressure cylinders, and thence to the low-pressure cylinders, and ultimately to the chimney with as direct a flow and as few changes of section as possible. In most of these engines the exhaust left the high-pressure cylinder at the front end of the piston-valve, and was conveyed in a straight pipe about 5 inches diameter and 3 feet long outside the frames forward to the hind end of the low-pressure piston-valve. It was very noticeable in some engines, where it had been difficult to make the same arrangement, in eight-coupled engines where the four cylinders were side by side, Fig. 40 (page 392), that one did not get so direct a flow, and there was a distinct change in the diagrams. In conclusion he might add that in a conversation on the previous day with M. du Bousquet, that eminent engineer told him that with their "Atlantic" engines they had repeatedly, with 300 tons behind the tender, run 30 consecutive miles at a regularly maintained speed of 75 miles per hour.

Table 20 (pages 390–391) gave the leading dimensions of various types of locomotives in France; and Figs. 41 and 42 (pages 394–397) showed the steam distribution and slide-valves of the H.P. and L.P. cylinders of the "Atlantic" and six-coupled ten-wheeled locomotives for the Paris-Orléans Railway.

Mr. JOHN F. ROBINSON, Member of Council, said he had been particularly interested with the diagrams, some of the figures given being most remarkable. One extraordinary result which it would be hard to beat in this country was the case of an engine with 350 tons, or thereabouts, behind the tender, which made an average speed of 58·8 miles an hour, including stops. With regard to the engine itself, whatever ideas engineers might have had in the early stages of four-cylinder compounds, he thought when they saw the figures on page 328 stating the number which had been produced in France and which were being used also in other countries on the Continent, there could be no doubt that the engines had come to stay, the result of the figures quite justifying that statement. There was one thing which had struck him forcibly, namely, that engineers seemed to be quite satisfied in France with a wheel 6 feet 6¾ inches (2 metres) in diameter for the express work, whereas in this country a great many engineers had nothing under 7 feet, and in some instances higher, for the really high speed work.

With regard to the two large Paris-Orleans "Atlantic" engines, the designs of which were given in Table 2 (page 333), the grate area there given was 33½ square feet. According to the photograph of the engine shown, the fire-box was between the frames, and the frames there could not be much more than 4 feet 1 inch apart, which meant that the inside width of the fire-box could not be much over 3 feet 6 inches. It seemed to him, if that was so, the inside measurement of the fire-box must be 9 feet long. He would like to ask the author if he had had any difficulty in firing with such an enormously long box, because it was no easy matter to fire a grate 9 feet long, even if it was standing still, but, of course, if the engine was travelling at 70 miles an hour it was a great deal worse.

There was another point on which he would like some information. The tubes were now getting to very great lengths, 14 feet 1 inch in one case and 14 feet 5 inches in another. He believed in all cases they were Serve tubes. He would like to ask if any difficulty had been found in keeping the tubes tight, because it had been found in this country that, when enormously long tubes were used, there was a good deal more bother in keeping them tight than the shorter ones. Engineers in this country did not use Serve tubes, and almost always used copper and brass tubes, although some people preferred steel and iron. He noticed (page 374) a reference to the difficulty which had been experienced with copper stays when dealing with high pressures and high temperatures. The same difficulty had been found in this country. He was glad to see that the use of manganese bronze had been satisfactory in meeting the case as far as stays were concerned. The Paper stated that so far no satisfactory material had been made for tubular plates, and he was curious to know if any manganese bronze plates had been tried, and if so with what results. Lastly, he desired to congratulate the author on the very fine engine shown on Fig. 3, Plate 50, the Eastern six-coupled compound. He thought it was one of the handsomest engines of the type he had

(Mr. John F. Robinson.)

ever seen. He heartily congratulated the author on his production. The author had exhibited a working model of the engine,* which showed very completely the way in which the engine worked, and especially the balancing, which the author had so well explained, and which, to his mind, was one of the most important features of that type of engine.

Mr. G. J. CHURCHWARD, Locomotive Superintendent of the Great Western Railway, wished most heartily to congratulate the author, Mr. de Glehn, and the other engineers in France who had put so much work and ability into the perfecting of the compound locomotive. There was no doubt in his own mind, and probably none also in those of the members present, that the compound locomotive had been developed to a point of greater perfection in France than in any other country in the world. It was his strong opinion to that effect which induced him to advise the Great Western Railway Directors to purchase one of those locomotives for experiment. A large number of so-called trials or tests between simple and compound locomotives had been made all over the world, but in his judgment no really fair and square tests between the advantages of compound and simple cylinder engines had ever been made. It would be found that some of the earliest tests between compound and simple locomotives which were made in this country were made between a compound engine, on the one hand, having 200 lbs. to the square inch in the boiler, and a simple engine having 175 lbs. per square inch. Quite naturally, the compound engine had the best of it, and that settled the point for the time. He was sorry to say that even in America that opinion still obtained to some extent, and in France also it had been the same. He would no doubt be told that the high pressures were used in the compound in the belief that it was impossible by any known valve-gear to use the same high pressures to advantage in a simple cylinder. He had thought that that had yet to be proved, and had had the courage to fit a simple engine with 18-inch by 30-inch cylinders, with a boiler carrying

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* Kindly lent by the Board of Education, South Kensington.

225 lbs. to the square inch. He had done that with the deliberate idea of finding whether such improvements could be made in valve-gear, and consequent steam distribution, as to enable the simple cylinder to use steam of that pressure as efficiently as the compound engine. With the farther view to make sure that the tests as between a simple and compound engine should be on quite equal terms, he had managed to arrange that the power—at any rate the powers at high speeds such as were now used for passenger trains—of the compound was practically identical with the power of the simple. It had been arranged that equal power should be given on the basis of a cut-off of the compound engine, as recommended by Mr. de Glehn, of 55 and 65 in the high and low pressure respectively, and a cut-off of something between 20 and 25 per cent. in the simple cylinders. It would seem no doubt ambitious to expect such power as was developed at 55 and 65 by the compound locomotive out of a cylinder in a simple engine cutting off at 20 to 25 per cent.; but he was pleased to say that with the assistance of an efficient staff, a good deal of very hard work, and a determination to see what was possible to be done with the valve-gear, he believed such improvements had been made in the steam distribution that a satisfactory result could be ensured from as high a cut-off as 15 to 20 per cent. In a test which had been made of the 18-inch by 30-inch stroke cylinders, of which he had been speaking, they had obtained, at 70 miles an hour, a draw-bar pull of 2 tons behind the tender. Upon a test which had recently been made with Mr. de Glehn's engine, "La France," that had also obtained a draw-bar pull of 2 tons at 70 miles an hour. The cut-off in the case of a compound engine was as advised, 55 and 65; and the cut-off in the simple engine was 25. The pressure used in the simple engine was only 200 lbs. to the square inch, so that in the simple engine carrying 225 lbs. to the square inch he thought it was legitimate to expect that the 2 tons at 75 miles an hour would be obtained with a rather higher cut-off than 25 per cent. The question which would immediately occur to all engineers was, what was the amount of steam used in the cylinders respectively on the two engines to give the pull of 2 tons at 70 miles an hour? The theoretical amount of

(Mr. G. J. Churchward.)

steam in the 18-inch by 30-inch cylinder with 25 per cent. cut-off was practically identical with that which there was in the high-pressure cylinders of the compound locomotive at the 55 cut-off; so that, if those figures were appreciated, engineers would no doubt understand that he had on foot, at any rate, means for a more equal trial between a compound and simple locomotive than had ever been made before. He would not like any one to take anything he was saying as to the results of trials between the French compound locomotive "La France" and engines on the Great Western as final or definite, because it would be obvious to any who had practical experience in the running of locomotives that for so short a space of time, and with so little mileage as they had been able to do with the engines, it was fruitless to give any definite opinion upon results. He was endeavouring in what he was saying to give no definite opinion as to the accomplished results.

The first question that would occur to an engineer's mind would be the relative coal-consumption. When one knew the various factors which went to make up high and low coal-consumption, one realised that nothing short of a 12-months' average was of any use in comparing the coal-consumption of one engine with another, and he did not propose to give anything of the kind. He would like to take the opportunity, as both Mr. de Glehn and M. Sauvage were present, to say that "La France" had been doing very first-class work indeed on the Great Western Railway. She had given every satisfaction, and had entirely fulfilled his expectations; the work she had been doing on some of the fastest trains was really very fine, and he thought had not been equalled by any of what he might perhaps be permitted to term the old-fashioned simple engine. Those present who had studied the actual draw-bar records, which to his mind was the only record that was worth talking about in regard to a locomotive, knew that a steady pull on the draw-bar at the back of the tender of 2 tons at 70 miles an hour on a 6-foot 6-inch wheel, took, if he might use a colloquialism, a great deal of getting, and when they had it, it took a good deal of keeping up. But it was fair to say that the Great Western had two or three engines running today that would do that, and "La France" was one of them.

A great deal had been said, and comparisons had been made upon what had been said, as to the weight of train which a particular engine would draw in a certain time between two points which were so far apart. From his experience he wished to caution any one from laying too much stress on such a comparison. A 300-ton train might, for example, be a train of 8 or 9 bogie carriages; it was about that on some lines; while in another case a 300-ton train might be one of about 13 bogie carriages, which was about what it was on the Great Western. It was obvious that in a wind, or round curves, and on almost any piece of line there was in the country, the traction required for a train of 13 bogie coaches was very different from that required for 8 or 9 coaches, so that such figures were really no guide in comparing the performance of locomotives. It was not possible, even to the greatest expert, to compare locomotives unless he happened to be riding in a dynamometer car at the back of the engine at the time; so that in any results which they were striving to get between the various engines they had under observation, they were basing the whole of their calculations upon observations made in a dynamometer car.

The force of what Mr. de Glehn said on the division of the engine was, he thought, very great. He was not sure that at present they had arrived at the limit of weight at which they must divide the engine, but he felt sure with Mr. de Glehn that if they had not arrived at it now, they would soon do so if the engine grew much bigger. The Americans had undoubtedly arrived at the point when they must divide the engine, and he hoped the success of Mr. de Glehn's engine, which was going over there to the St. Louis Exhibition, would result in the whole subject being enquired into by American engineers, in much the same way as he believed it was being done today in this country.

There was one defect about the compound engine which gave him, he thought, more disappointment than any other, namely, that it did not get over boiler troubles. As a man having the care of a great many engines, he did not mind much what the engine did; he could always look after the engine; it was the boiler that troubled him. In the compound engine one felt that he must use a high

(Mr. G. J. Churchward.)

pressure; he was not quite sure that that was necessary, but at any rate it was universal up to the present; and whilst they were still obliged to use such a pressure as 225 lbs. to the square inch, he believed that the progress of the compound principle would be checked very largely among locomotive engineers who feared trouble with the boilers. The Great Western were facing the trouble, and had a large number of boilers running today at 200 lbs. to the square inch; and in some cases, at any rate, there was evidence that the increase of trouble with the higher pressure was not quite so much greater than they had been led to expect. But still there it was, and it was impossible to get rid of it. The fact had been mentioned frequently that the divided engine and four cylinders gave a more equal torque on the shafts. He might be very dense, but he had been unable to realise that up to the present. If there were two cylinders exactly opposite one another at 180°, and the same steam distribution was used as with one, he hardly saw how the torque on the shaft could be otherwise than the same in each case. He would conclude by saying that he thought some of the advocates of compounding had perhaps laid too much stress on the fact that the same power could not be got at high speed out of a simple locomotive without using excessively large cylinders. The Great Western had already gone far enough to prove that one could get the necessary power without going beyond an 18-inch cylinder, and whilst the cylinder diameter was restricted to 18 inches, the stresses were really no greater on the big end and on the shaft than the dimensions they were able to provide would meet.

Mr. W. M. SMITH thought it was highly interesting to know what had been done by locomotive engineers in France. He felt indebted to the author for the valuable information given in connection with the work done by compound locomotives across the Channel. His personal experience with compound locomotives dated back about eighteen years. On a future occasion he might have something to say about compound locomotive engines in England. The author stated in his concluding remarks on page 378: "Compound locomotives or any other engines must be used under proper conditions of service to be economical. Powerful locomotives must have sufficiently heavy weights to haul, or else they become wasteful." He agreed that that was the general rule; he had always held that, just as there were exceptions to every rule, so it was possible to have compound locomotives that would work light or heavy trains at an economical coal-consumption. By the courtesy of Mr. S. W. Johnson he was enabled to give interesting particulars and diagrams of the working of a light train by one of the Midland Railway compound engines, No. 2631, Fig. 43 (pages 406 and 407); the train hauled weighed 272 tons, the coal-consumption being 23·3 lbs. per mile, which worked out at 0·0856 lb. per ton-mile, and gave a consumption of 2·16 lbs. per I.H.P. per hour. Those figures were exceptionally good, as the ordinary average of a small simple engine would not, as a rule, be less than 3 lbs. of coal per I.H.P. per hour.* Statements without being substantiated by facts were misleading. It was common practice for locomotive engines to pull trains weighing 465 tons in one direction, and on the return journey to work trains weighing 272 tons, engine and tender included. He had designed a four-cylinder compound locomotive, the system and arrangement of the compounding being on the same principle as that employed in the engines of his three-cylinder system, the main difference being that four cylinders were used in the place of three. The distributing valves in the case of the four-cylinder engines might be driven by alternative arrangement of valve-gear, one of which was a modification of the Stephenson principle, and the other a modification of the Walschaerts principle.

Mr. Vaughan Pendred said that as he was not a locomotive man it was not his intention to occupy much of the time of the meeting. He wished that more locomotive engineers had been present to hear the Paper. His particular object in speaking was for the purpose of asking questions. He wished to know how far the external characteristics of locomotives affected their performance. It had so chanced that during the last eight or ten years he had very carefully watched the performances of locomotives of this country and abroad.

(*Continued on page* 408.)

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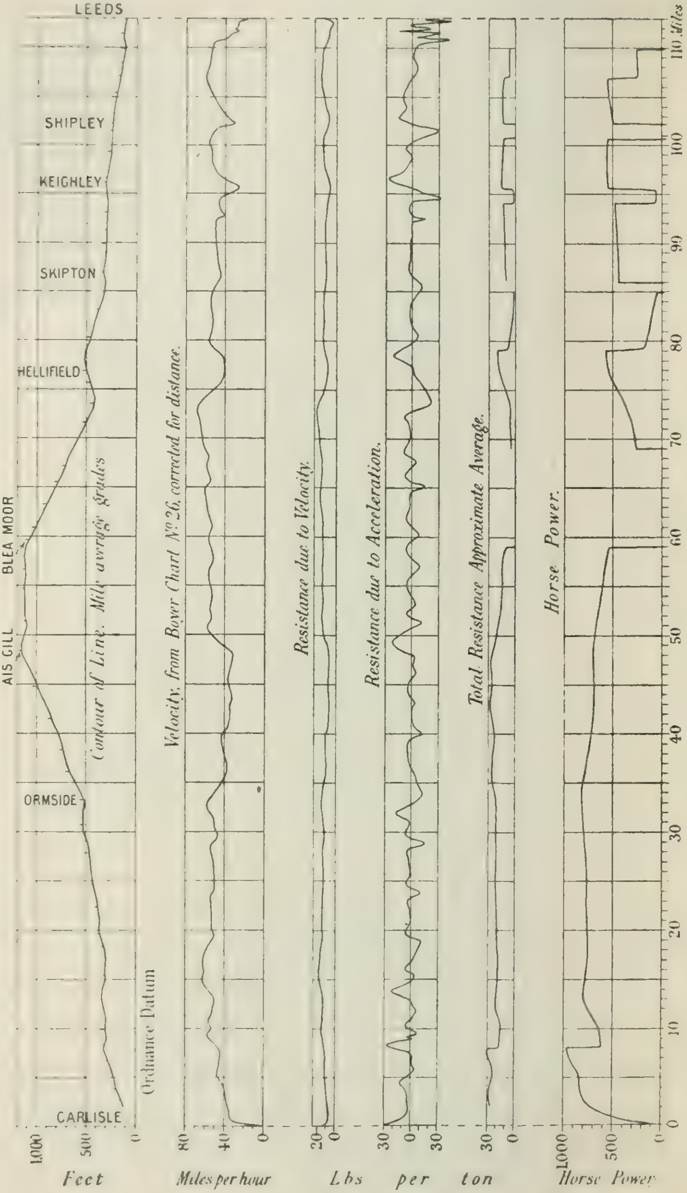
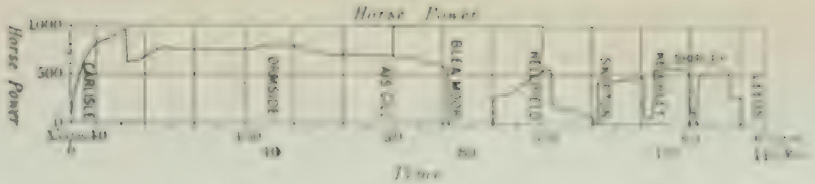
* Proceedings 1898, Part 4, page 521.

(Mr. W. M. Smith.)

FIG. 43. 3·55 p.m. *Express Passenger Train from Carlisle to Leeds.* 27 *Oct.* 1902. *Midland Ry.*
Worked by 3 *Cyl. Compound Engine.* No. 2631. *Load,* 6 *carriages* = 10½ *units.*





Total Weight of Train, 272 tons.

Water.

Total, 2,750 gals. Per H.P. per hour, 22·5 lbs. Per Mile, 243·4 lbs. Per Vehicle-Mile, 23·2 lbs. Per Ton-Mile, 0·895 lbs.

Coal.

Total, 23·5 cwts. Per H.P. per hour, 2·16 lbs. Per Mile, 23·5 lbs. Per Vehicle-Mile, 2·22 lbs. Per Ton-Mile, 0·0863 lbs. Water used per lb. actual, 10·45 lbs. Water used per lb. equivalent from and at 212° F., 12·62 lbs.

Quality.

½ Manvers, ½ Featherstone. Moisture contained, 2·29 per cent. Ash, 2·15 per cent. Calorific Power, 14·0 lbs. water.

Average Horse Power, 520.

Average Horse Power to Blea Moor, 725.

Average Speed, 48·45 miles per hour.

Coal and Water used to Blea Moor, 75 per cent.

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and if Mr. de Glehn would permit him to say so without offence, he had seen with considerable distaste and dislike that English engines had been apparently beaten by French engines. He did not suppose any locomotive performance had ever been accomplished in England equal to what had been done with compound engines on the Northern Railway of France, according to the Paper which they had just heard. It had been simply superb. A good deal had been heard during the discussion of the four-cylinder compound, and about what it could do. The four-cylinder compound had been used in this country for a long time, but it had not accomplished what had been done in France. He did not know whether a representative of the London and North Western Railway was present, but he thought that company had carried the art of piloting, even with four-cylinder engines, to perfection. On one occasion Mr. Webb, at the Institution of Civil Engineers, was twitted with the fact that so much piloting was done on his railway, but he replied that it was not his fault, but that of the Traffic Manager, who insisted upon it. Even with the piloting, the four-cylinder compounds were not keeping time; perhaps the time was too small, and it was not the fault of the engines. But when one examined into the general results of the work, there must be some latent reason why it was that some locomotives did so much better than other locomotives did.

One of the first points that occurred to him in connection with the French performance was that possibly the resistance which the engines had to overcome was less than it was on the English lines. He remembered asking Mr. Whaley, who was at the time district locomotive superintendent of the Western Railway of France, some questions in regard to that matter, and he told him it was found necessary that the springs on the French locomotives and coaches should have about twice the range they had in this country. Was it a fact that the absolute train-resistance was less in France than it was in this country as a result of the elastic springing? That was one point on which he wished to have some information.

He thought it might generally be assumed that there was a certain speed for a locomotive at which the engine could be run at which there would be no pull at all; she would run until she could do no further pulling. He had received a letter from Mr. Ivatt of the Great Northern Railway on that particular subject a short time ago, in which he stated that the drivers were the men who practically knew most about what the engines could do. If a driver had to take a train up to 50 miles an hour, he liked the small-wheeled engine, but as soon as he had to go above 50 miles an hour he liked the large-wheeled engine. That went to show that the resistance of the engine itself played a very important part. In speaking recently to Mr. Aspinall on that very subject, that gentleman said that the grand improvement which had to be effected in the locomotive was to make such an arrangement that the ends of the cylinders could be taken clean out at each stroke, as to free the exhaust. Every engineer knew that the difficulty was not in getting the steam into the cylinders, but in getting the steam out of the cylinders. If then it could be shown that there was some particular speed at which particular types of locomotives ran till they had practically no pull on the draw-bar, he thought it was highly desirable that they should get, what might be called, the internal resistance of the locomotive not regarded as a vehicle. Regarding the locomotive as a vehicle, if the cylinder-cocks were opened it would be found that one locomotive could haul three locomotives by itself as a train with about the same ease as a loaded train of the same weight; but that was not the point. What they wanted to arrive at was, what was the actual internal resistance of different types of locomotive with steam in the cylinders. He had been writing to friends all over the country in the endeavour to find out if any engineer had ever taken diagrams from a locomotive running light at high speeds. Plenty of diagrams had been taken of light locomotives running at low speeds. Some engineers would say: "What would be the use of it? It would be simply a line." Others would say, "No, we have never done it at all." His friend Mr. Drummond, of the South Western Railway, had very kindly responded to his enquiry, and had asked at what speeds he desired to have the diagrams made, and he would then have them taken. He did not know whether the meeting would be adjourned, but if so, and he received the diagrams from Mr. Drummond, he would have

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much pleasure in sending them to the Institution, and he hoped they would prove very interesting.

He would like to know from the author and Mr. de Glehn, whether they had any precise results showing what the effect at high speeds of particular types of engines might be on the draw-bar pull, that is, if a six-wheeled engine or a four-wheeled engine, as the case might be, were taken, what the actual results with regard to the draw-bar pull were. He thought the results given in the course of the discussion, 2 tons at 70 miles an hour, were simply magnificent. Could that result be best obtained from the six-coupled or four-coupled engines? He would like to know, in fact, what type of engine gave the best net result in draw-bar pull, which was, after all, the real test for engineers to have, at the various speeds which were required. At the present day the highest speeds that could be obtained were wanted. It had given him immense pleasure to hear Mr. Churchward say that he believed he could get as good results out of a non-compound as he could out of a compound engine, because he had long been a believer in that type of engine.

It might be worth while to refer to the fact, on the Midland Railway Mr. Samuel Johnson tried some large cylinders in conjunction with very small boilers, the results being unsatisfactory, and he had to line the cylinders up; but the fault was not the engines' nearly so much as it was the drivers', who when they had the engines on the banks ran them out of breath. If any valve-gear could have been provided which would have prevented that happening, he believed the result would have been very much more satisfactory than it was. [*See also page* 428.]

Mr. J. W. SMITH thought that from what had been said by the author, and by the remarks that had fallen from Mr. de Glehn, that French engineers had made a very great success of the compound locomotive. It had often occurred to him to ask, when French engineers had been so successful with four-cylinder compound locomotives, why it was that English engineers, at least judging by results, had not to any extent favoured that type of engine. As a possible explanation he had been told that prior to the advent of the compound locomotive in France, the trains there had not run at so high speeds, nor were the engines so powerful as they were in England. In France the compound locomotive was introduced at the right time. It performed work which the older simple type of engine had not done, consequently earning a reputation which had brought it to the front. On the other hand, engineers in England appeared to be satisfied with the simple engine, holding the opinion that it could be considerably improved. He noticed that Mr. Churchward's opinion still tended in that direction.

Mr. Churchward said he gave no opinion with regard to results at present.

Mr. J. W. Smith said he did not imply that for a moment; what he meant was that Mr. Churchward had still sufficient faith in the simple engine to design and build one having a boiler of similar capacity, and the same working pressure as the French compound he was going to test it against—the two engines to be worked under similar conditions as near as could be obtained.

He would like to refer to the diagrams on page 346. In these very interesting indicator diagrams one thing was noticeable, namely, the remarkable steam line on the diagrams taken from the high-pressure cylinders at the higher speeds. It would have been useful if the author had given information as to the weight of the engine and tender, and also as to whether, when the diagrams were taken, the speed was accelerating or falling off. If this information had been given, it could, by a simple calculation, have been ascertained whether the trains in France required more power per ton to draw them than those in this country. As Mr. Churchward had said, a short train took less pulling than a long one of the same weight, and the speaker thought that was perfectly correct. Assuming the mean weight of the engine and tender to be 108 tons, if he were allowed he would make a comparison with the figures which had been experimentally ascertained of the power absorbed by the passenger rolling stock on the Midland Railway. On that

(Mr. J. W. Smith.)

railway Mr. Deeley had carried out a large number of experiments and formulated a train-resistance curve. The figures he would use might not be quite the same as those adopted by Mr. Deeley, but in any case they would only vary slightly. He would assume the train-resistance, including engine, tender and train, in lbs. per ton on the level as being equal to $3 + \frac{V^2}{250}$. Referring to the starting diagram, *i.e.* the one at the top of the left-hand column on page 346, the load on the tender draw-bar was given as 3·33 tons, which was equivalent to about 23·5 lbs. resistance per ton of train. Using the assumed weight of 108 tons, the resistance worked out at about 82·5 lbs. per ton for the engine and tender alone. This meant that the engine and tender absorbed about 3·5 times as much power per ton as the train. Referring to the other three sets of diagrams on the same page, a comparison of the indicated horse-power, with the pull on the tender-coupling showed on the average that the engine and tender absorbed per ton just over twice as much power as the train. Again, referring to the lower set of diagrams in the left-hand column of page 346, the power available for the total moving weight worked out at 16·4 per ton. The speed of the train was given as 60·8 miles per hour, and to maintain that velocity by the formula he had mentioned would require a force of 17·8 lbs. per ton, and assuming that the French rolling stock offered the same resistance to motion as the Midland Railway rolling stock, then the difference—1·4 lbs. —would indicate that the French train in question, at the time the set of diagrams was taken, was losing speed at the rate of 0·76 mile per hour per minute. In the last set of diagrams at the bottom of page 347, after making allowance for the gradient, the indicated horse-power gave an available power of 10·6 lbs. per ton for the total moving weight, whereas, to maintain the speed of 54·3 miles per hour, he reckoned by the formula that a power of 14·8 lbs. per ton would be required, and making the same assumption as in the previous case, he calculated that the engine was losing speed at the rate of 2·2 miles per hour per minute. All the other diagrams, with one exception, gave like results; in the most extreme case the engine appeared to have been losing speed at the rate of 6·3 miles per hour per minute. The exception mentioned is found in the set of diagrams given in the right-hand column at the top of page 347, where it was stated that the train was running down a gradient of 1 in 200 at a speed of 77 miles per hour. He calculated that the speed in this instance was accelerating approximately at the rate of 2·6 miles per hour per minute. If the author could state whether the engine was losing or gaining speed and give the rate of change of velocity when the diagrams were taken, he thought some idea could be formed as to whether the French rolling stock took less pulling than ours, and he believed that the information would be interesting and acceptable to most railway engineers.

The four-cylinder compounds had certain advantages, but he failed, like Mr. Churchward, to see how it was that the turning effort was more uniform than in the case of a two-cylinder engine. He believed that when marine engineers designed an engine they preferred an odd number of cranks, and he thought that the three-cylinder engine as regards turning effort might have advantages which the four-cylinder engine did not possess. With regard to the arrangement of the four-cylinder compound mentioned in the Paper, there were two high-pressure cylinders placed outside the frames fairly well back, and two low-pressure cylinders placed inside the frames fairly well forward. This arrangement necessitated pipes passing down from the dome outside the boiler to the high-pressure steam-chests, and when the steam was exhausted from these cylinders it had to pass along through pipes placed outside the frames to the low-pressure chests. The number of pipes and their position seemed to him to be conducive to condensation. With the three-cylinder engine, such as Mr. Johnson had designed for the Midland Railway, the high-pressure steam passed through one large pipe inside the smoke-box where it was kept warm by being surrounded by gases having a higher temperature than the steam; then, when the steam was exhausted from the middle cylinder it had to pass through no pipes at all, but went directly into the low-pressure steam-chests.

(Mr. J. W. Smith.)

Although he had not very much experience of French engines, he had had the pleasure of riding several times on them, and he noticed that the condensation was fairly heavy in the low-pressure cylinders. On the Midland Railway the engines gave very little trouble indeed with condensation. There were other points in the French engines to which, if time had permitted, he would have liked to compare with those in some of the most successful types of compound locomotives in this country. The Midland engines had done some most remarkable work; one of those recently built started running on the 4th November last, since when, he believed, it had worked daily, including Sundays after the first week, and the mileage up to the present time averaged 6,800 miles per month. He thought that the work done by that engine went to show that the compound engine, whether it had three or four cylinders, could run and keep out of the shops. He believed that about Christmas time the engine successfully worked trains of 350 tons behind the tender, and trains of a weight which could not have been successfully worked with an ordinary engine; in fact, for many days together it might be said that the use of a pilot engine was avoided. The trains referred to were worked between London and Leicester, the average booked speed being 52 miles per hour, but in many instances the actual mean speed was considerably higher.

M. LAURENT, Assistant Locomotive Superintendent of the Paris-Orléans Railway, speaking in French, said that he had followed with great interest the discussion which had just taken place. The Paris-Orléans Railway Co. had used four-cylinder compound locomotives since 1899. These locomotives were identical with those already used for several years by the Northern and Southern Companies, namely four wheels coupled with bogie. They had drawn their heaviest express trains, from 1899 to 1903, over gradients not exceeding 1 in 125. At about the same time some four-cylinder compound locomotives with six wheels coupled were also brought into service which took their express trains on the central French lines (Paris to Toulouse, Paris to Montauban, Bordeaux to Lyon), where there were gradients 1 in 66 to 1 in 50. These locomotives had given great satisfaction.

The weight of their trains was always increasing. They had to run on their line, principally from Paris to Bordeaux, which is a distance of 580 km. (360·40 miles), trains travelling at 90 and 95 km. (55·92 and 59·03 miles) an hour of effective average speed, and having between Paris and Tours a load of 250 t. to 300 t. (246 to 295·2 tons). To be able to keep time on these trains, they were obliged to attain an effective speed of from 100 to 110 km. (62·138 to 68·3 miles) an hour on the level or on gradients of from 1 in 333 to 1 in 200. The engines built in 1899 no longer gave a sufficient margin to allow of lost time being made up. Consequently they were induced to consider the use of more powerful locomotives, as they had attained the load-limit of 18 tons per axle. Mr. de Glehn had built for them some "Atlantic" and six-wheel coupled engines, Fig. 44 and 45, Plate 65. These engines were identical in boilers, cylinders, &c.; only they differed in the number of coupled wheels and the diameter of the wheels: 2 m. (6 feet 6¾ inches) for the "Atlantic" engines, 1·8 m. (5 feet 11 inches) for the six-wheel coupled engines. Finally, they were now having built with the same boiler, eight-wheel coupled engines with leading pony truck, Fig. 46, Plate 65; these were intended to run goods trains on the various lines in the centre of France.

His friend, M. Sauvage, had given all the information about their new four-cylinder compound locomotives, and he would only add two points from his own experience. The first was in reply to a question by a previous speaker in reference to the great length of their fire-boxes (page 399). These were 3·10 m. (9 feet 10½ inches) in length; before putting the engines into service their attention was occupied by considering the most suitable slope for the grate, to permit the sliding down of the coal. These engines had caused no difficulty since they were started about a year ago. There had been burnt in them as much as 550 kg. of coal per square metre (112¾ lbs. per square foot) per hour, and they made the journey from Paris to Tours, 238 km. (147·88 miles), and from Tours to Bordeaux, 350 km. (217·48 miles), with the same shift. The coal should be placed on the back part of the grate, whence it would slide down the grate. Naturally, they employed their best stokers for these trains, and they had experienced no difficulty.

(M. Laurent.)

The second experience he wished to mention was that in 1902, with engines of the previous type, they had been obliged to divide their Paris-Tours quick trains up into two parts, during the whole of the summer, that is to say for nearly three months. In 1903 during the same period their new engines had enabled them to run all these trains without dividing them.

Discussion on Friday, 15*th April* 1904.

The PRESIDENT reminded the Members that at the last meeting an important discussion on M. Sauvage's Paper was commenced, and the discussion about to be resumed would be equally important. Some of the leading locomotive superintendents of the country had taken the trouble to send diagrams, which, in the course of the discussion, would be alluded to, and some who had been unable to be present that evening had been so much interested as to send written communications on the subject, which would be communicated in brief, and would be published in full in the Proceedings. Mr. Samuel Johnson had written a valuable communication of which the Secretary would read some extracts.

Mr. HENRY A. IVATT, Member of Council, said that, as he had been unable to be present at the last meeting, he had not had the pleasure of joining in the vote of thanks to the author proposed by the President before the discussion began, but he desired to take this opportunity of testifying his appreciation of the very excellent Paper which M. Sauvage had contributed to the Institution, and to thank him, not only for writing it in English, but for so thoughtfully translating the speeds into miles per hour, and the pressures into pounds per square inch. He would not attempt to touch upon many of the points of interest suggested by the Paper, but proposed to refer briefly to an experiment he had made in compounding about ten years ago, and then to say something on engine-resistance and draw-bar pull.

About the year 1894–95 he compounded two engines on the Great Southern and Western of Ireland. One was a six-wheeled coupled goods, and the other a four-coupled express engine. As simple engines, both had inside cylinders 18 inches by 24 inches; they were compounded on the Worsdell and Von Borries system with high-pressure cylinder 18 inches and low pressure 26 inches, the stroke in each case remaining as before, namely, 24 inches. The goods engine had a flap intercepting-valve, and the express engine had a change-valve of his own design, allowing the engine to be worked as a non-compound when required. The steam-pressure in both was kept the same as before compounding, namely, 160 lbs. per square inch, with a view to seeing whether compounding alone produced any improvement. He left the Great Southern Railway in 1896, but understood that the engines remained at work until they required new cylinders, when they were re-cylindered as simple engines. The net result of the experiment was that *as compounds* the engines were *no better* and *no worse than they were before*. The engines on which this experiment was made were of moderate size, and it did not follow that for a more powerful engine the compound four-cylinder or other type would not show to greater advantage.

The experiments now being carried out on the Great Western between compound and simple were of great interest and value, because the conditions as to steam-pressure, etc., were nearly identical; but he thought the trials would be still more interesting if the simple engine had the same arrangement of cylinders, cranks, wheels, etc., as in the compound, the cylinders being of such dimensions as to make the nominal tractive force of the two engines about equal. The measure of the useful work being done by a locomotive at any time was the draw-bar pull at the back of the tender. Indicator diagrams might give the horse-power being developed in the cylinders, but they would not show what horse-power was delivered to the train in the shape of draw-bar pull, particularly at high speeds, because more or less of the cylinder

(Mr. Henry A. Ivatt.)

horse-power was required to overcome the resistance of the engine itself.

The resistance of the locomotive tended to increase and the draw-bar pull to decrease with increase of speed, so that for every engine there was a maximum speed at which it would only move itself, leaving no pull available at the draw-bar. Diagram Fig. 47 (page 419) gave the draw-bar pull of two engines at various speeds. The fine line was from an eight-coupled engine with small wheels, intended to work heavy coal and goods trains, at an average speed of about 20 miles an hour. The thick line was from a single-wheeled express engine. The initial pull in this case was not nearly so great as with the other; but after about 30 miles an hour, the single-wheeled engine showed the best pull. The diagram was made from records obtained in regular service, and therefore must not be taken as representing the highest efforts of which the two engines were capable at all speeds, but rather as illustrating the *relative falling off in draw-bar pull* with two different types of engines as the speed increased.

The single-wheeled express engine, which at starting was only capable of putting on a draw-bar pull of about half as much as the eight-coupled engine, was able to put on the greater pull at higher speeds, say from about 30 or 40 miles an hour and upwards. This diagram illustrated two extremes, but it indicated the reason why some express engines with nominally small tractive force often did so well with heavy trains at high speed, and it also helped to show why drivers working trains timed at high average speed would always go for what they called a "free running engine"—by this expression they meant the engine which gave the best draw-bar pull at the higher speeds, and the engine which did that was the one which consumed the smallest amount of power in moving itself, and left the most for the draw-bar. The increased tractive force required, by reason of the increased weight and speed of express trains, had led to the use of larger cylinders, but larger cylinders with high piston-speed meant more back-pressure, and consequently increased internal resistance. Dividing the work between four cylinders enabled them to be kept small, the reciprocating weights balanced

Fig. 47.

Draw-bar pull at various speeds.

— Compound goods.

— Single-wheeled express.

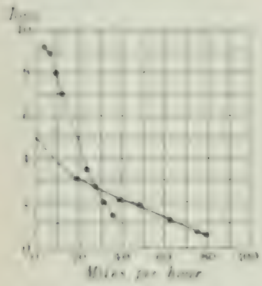


Fig. 48.

Tractive Power of Locomotives.

Prof. Goss ("Railroad Gazette," 17 Jan. 1902).

T = Tractive force at drivers.

t = Draw-bar pull.

$T = 191\frac{H}{S}$.

$t = 192\frac{H}{S} - 2\cdot 4\frac{d^2L}{D}$ − [illegible]

H = Square feet of heating surface.

S = Speed in M.P.H.

d = Diam. of pistons in feet.

L = Stroke in feet.

D = Diam. of drivers in feet.

W = Weight of engine and tender less weight of drivers.

Indicator Diagrams from Loco. No. 251, Great Northern Railway.

Fig. 49.

Weight behind tender 277½ tons. Speed 17 M.P.H. Draw-bar pull 5·5 tons. Gradient 1 in 200 up. Cyl. H.P. [illegible]. Regulator full open. Draw-bar H.P. [illegible]. M.E.P. [illegible] lbs. Difference H.P. 142·1. Mean Back-Pressure 6 lbs.

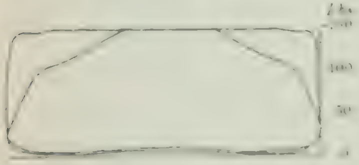


Fig. 50.

Weight behind tender 277½ tons. Speed 45 M.P.H. Draw-bar pull [illegible] tons. Gradient 1 in 200 up. Cyl. H.P. [illegible]. Regulator full open. Draw-bar H.P. 672. M.E.P. [illegible] lbs. Difference H.P. [illegible]. Mean Back-Pressure 7 lbs.

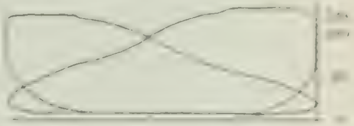


Fig. 51.

Weight behind tender [illegible] tons. Speed [illegible] M.P.H. Draw-bar pull [illegible] tons. Gradient level. Cyl. H.P. [illegible]. Regulator ¾ open. Draw-bar H.P. [illegible]. M.E.P. 58·1 lbs. Difference H.P. 361. Mean Back-Pressure [illegible] lbs.

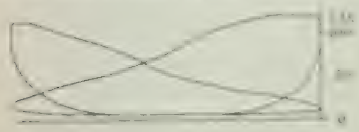
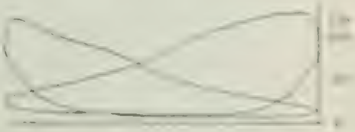


Fig. 52.

Weight behind tender [illegible] tons. Speed [illegible] M.P.H. Draw-bar pull [illegible] tons. Gradient 1 in [illegible] down. Cyl. H.P. [illegible]. Regulator full open. Draw-bar H.P. 538. M.E.P. 57·7 lbs. Difference H.P. 654. Mean Back-Pressure 9¼ lbs.



(Mr. Henry A. Ivatt.)

each other, so that no excess balance was required for this purpose; consequently there was no vertical disturbance, and this again helped to diminish internal resistance. With four cylinders there was of course the increased friction due to additional parts, but he thought that this might be more than compensated by the advantages mentioned. Another factor affecting internal resistance was the throw of the coupling-rods. The drivers' ideal of a "free running engine" was a single wheeler, and most engineers would do without coupling-rods altogether if they never had to run trains weighing more than about 150 tons over a moderate road. Being obliged to use coupling-rods, it was advisable to avoid swinging them about more than was necessary, and therefore the throw of the coupling-rod pins should be kept as small as possible. The circumference of the circles described by coupling-rod pins ranged from 7·8 feet with a 15-inch throw down to 4·7 feet with a 9-inch throw. Several express engines were running with a 9-inch throw for the coupling-rod pins. He himself used 10-inch for inside cylinder engines on the Great Northern Railway, and he was sure that keeping down the throw of the coupling-rods had an important effect on the internal resistance of the engine. He believed that the success of the express engines so well described by M. Sauvage was largely due to increased boiler power and the arrangement of the cylinders, apart from the compound principle; but to whatever cause it might be due, they all admired the very excellent work done by these locomotives, and congratulated their brother engineers on the other side of the Channel upon the success which they had attained.

With regard to the extra complication introduced by the use of four cylinders instead of two, it had been stated more than once that with modern high-speed locomotives, it was the boiler and not the engine which gave trouble, so that some extra complication on parts which (when well designed) gave little or no trouble need not be feared.

On diagram Fig. 48 (page 419) he gave a formula by Professor Goss for calculating the draw-bar pull of a locomotive at various speeds. It was published in the Railroad Gazette for 17th January 1902, and was derived from the experiments at Purdue University, which experiments were referred to by M. Sauvage (page 328). It would be noticed that the formula turned more on the speed and the heating surface than on size of cylinders or steam-pressure. Mr. Sturrock said that the power of a locomotive was "measured by its capacity to boil water," and his practice of fifty years ago indicated that he had acted upon that opinion, and modern practice showed the opinion to be sound. It had always struck him (Mr. Ivatt) that attempting to measure the power of locomotives by the size of cylinders was like trying to arrive at the relative spending capacity of two individuals by comparing the size of the purses they carried without reference to the state of their respective bank accounts. Moderate-sized cylinders were capable of doing a great deal of work, if well supplied with plenty of steam. In his "990" class of engine (Atlantic type) the cylinders were nominally 19 inches by 24 inches (actual diameter when new 18¾ inches), and these with 6-foot 6-inch wheels gave a piston speed of about 1,030 feet per minute at 60 miles per hour. The slide-valves were balanced with Richardson's strips, and the backs were open so that the exhaust had a free passage straight through the valve. Diagrams Figs. 49 to 52 (page 419) showed that the back-pressure was not excessive. The diagrams were taken from some records of work done by the Great Northern engine No. 251; this engine had a boiler with 2,500 feet of heating surface, and he had selected these diagrams as being somewhat comparable in point of speed, etc., with the four given by M. Sauvage, Fig. 16 (page 346).

Adding to the size of cylinders with a view to obtaining increased power did not result in much gain, if the effect of increased volume were to augment back-pressure, so as to neutralise any advantage secured on the driving side. Increase in back-pressure caused by enlarging the piston acted on the whole area, while the gain on the driving side was only that due to the additional annular ring, representing the increase in diameter. Many locomotives had been over-cylindered, and disappointment in their working has been due more to the cylinders being too large for the boilers than to defect in the method of handling the engines while at work.

(Mr. Henry A. Ivatt.)

The men who worked heavy trains—drivers and firemen—got by constant practice to exhibit the greatest skill in converting the latent energy of the coal in the tender into active energy or draw-bar pull by means of the machine which they handled for this purpose, and they knew how to accomplish this with the smallest expenditure of coal and water. When a driver had to make a run (say) of about 100 miles with an express train under conditions such that with care the water would just hold out, but that if his engine was not worked to the best advantage it would be necessary to stop for water before the end of the run, how did he work the engine? The text books indicated that he should run with the throttle wide open, and regulate the steam required in the cylinders by altering the point of cut-off with his reversing gear, or in other words, that he should work the steam as expansively as possible; but the driver knew that if he did this, he would use more water (and consequently more coal) than he would if he ran with the cut-off at the point which the engine *likes best*, and he regulated the supply of steam by wire-drawing at the throttle. He did not profess to explain scientifically the reason for this, but the fact remained, and it might help to reconcile them to the failure of various improved valve-gears (so-called) which had been tried at different times. A locomotive fitted with complicated gear, which produced diagrams with beautiful square corners, was, he believed, no better in practice than one with the old link-motion, which very possibly turned out a diagram shaped like a leg of mutton.

The PRESIDENT said that Mr. George Whale, the Locomotive Superintendent of the London and North Western Railway, hoped to have been present, but he had been obliged to return to Crewe. However, he had forwarded some diagrams, which were exhibited in the room, and the Secretary would briefly explain the points in connection with them.

The SECRETARY said that Mr. WHALE, who regretted he could not be present, had recently designed a simple express four-coupled bogie engine, with driving wheels 6 feet 9 inches diameter, and cylinders

(*Continued on page* 428).

Fig. 53. *Indicator Diagrams from the Locomotive "Precursor," L. & N. W. Ry., 27 March 1904.* (See pages 424–425.)

Up Trip, Crewe to Rugby.

Diagram No. 2.

Reversing wheel [illegible] turns back.
Speed = [illegible] miles per hour = [illegible] revs per min.
Gradient = 1 in [illegible] up.
Mile post = [illegible] from London.

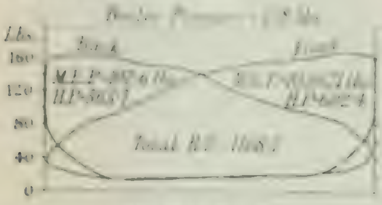


Diagram No. 5.

Reversing wheel [illegible] turns back.
Speed = [illegible] miles per hour = [illegible] revs per min.
Gradient = 1 in 177 up.
Mile post = [illegible] from London.

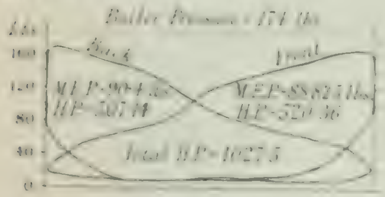


Diagram No. 18.

Reversing wheel [illegible] turns back.
Speed = [illegible] miles per hour = [illegible] revs per min.
Gradient Level.
Mile post = [illegible] from London.

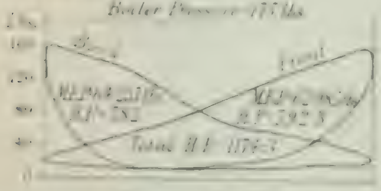
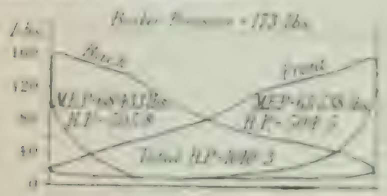


Diagram No. 26.

Reversing wheel [illegible] turns back.
Speed = 50 miles per hour = 207 revs per min.
Gradient = 1 in [illegible] up.
Mile post = [illegible] from London.



Down Trip, Rugby to Crewe.

Diagram No. 31.

Reversing wheel [illegible] turns back.
Speed = [illegible] miles per hour = [illegible] revs per min.
Gradient = 1 in [illegible].
Mile post = [illegible] from London.

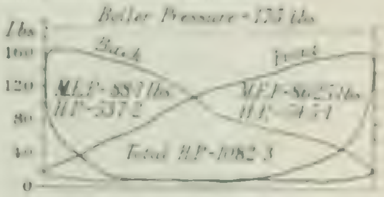


Diagram No. 32.

Reversing wheel [illegible] turns back.
Speed = [illegible] miles per hour = [illegible] revs per min.
Gradient = 1 in [illegible] up.
Mile post = [illegible] from London.

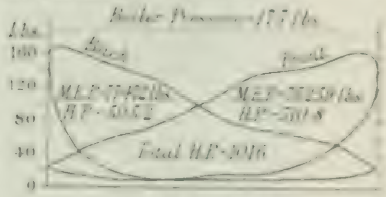


Diagram No. 33.

Reversing wheel [illegible] turns back.
Speed = [illegible] miles per hour = [illegible] revs per min.
Gradient Level.
Mile post = [illegible] from London.

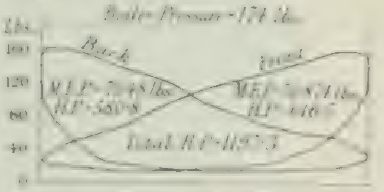
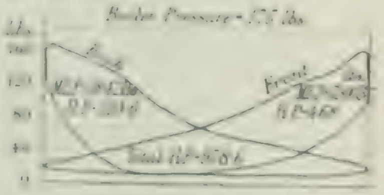


Diagram No. 43.

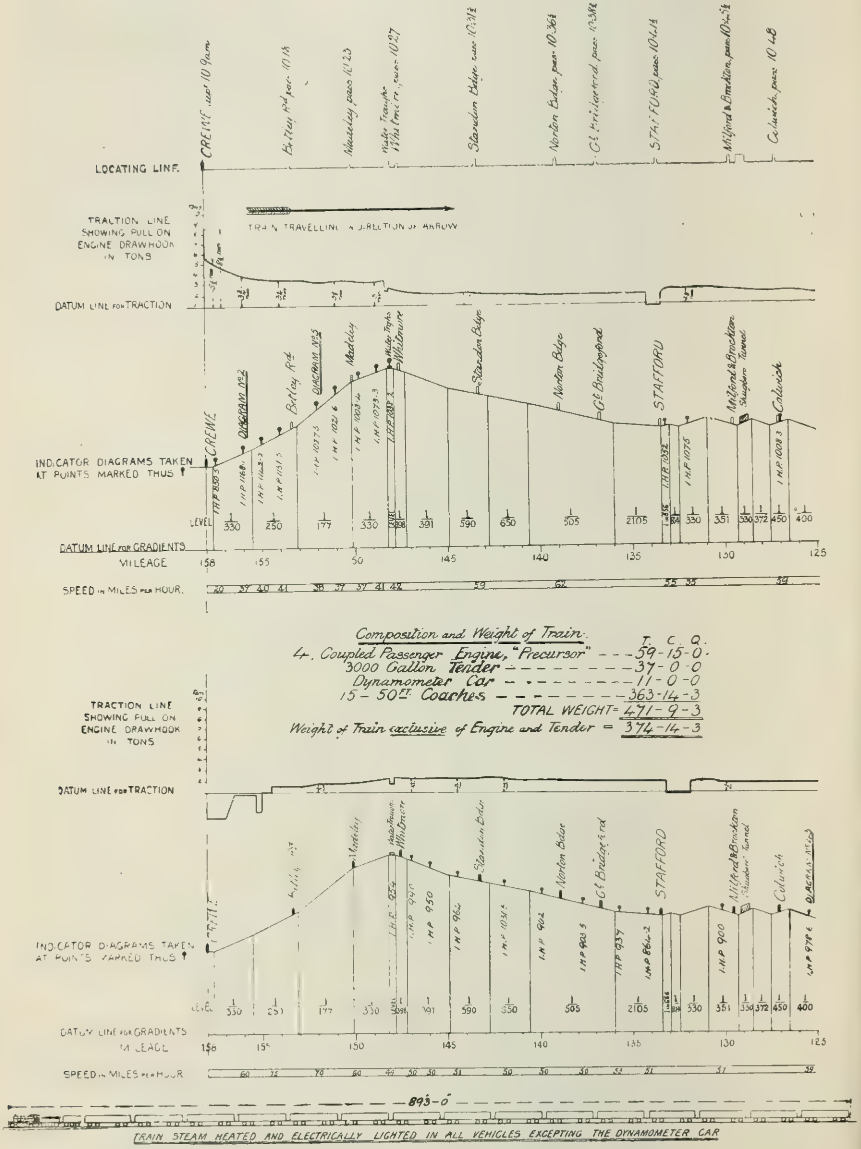
Reversing wheel [illegible] turns back.
Speed = [illegible] miles per hour = [illegible] revs per min.
Gradient = 1 in [illegible].
Mile post = [illegible] from London.



(Mr. George Whale.)

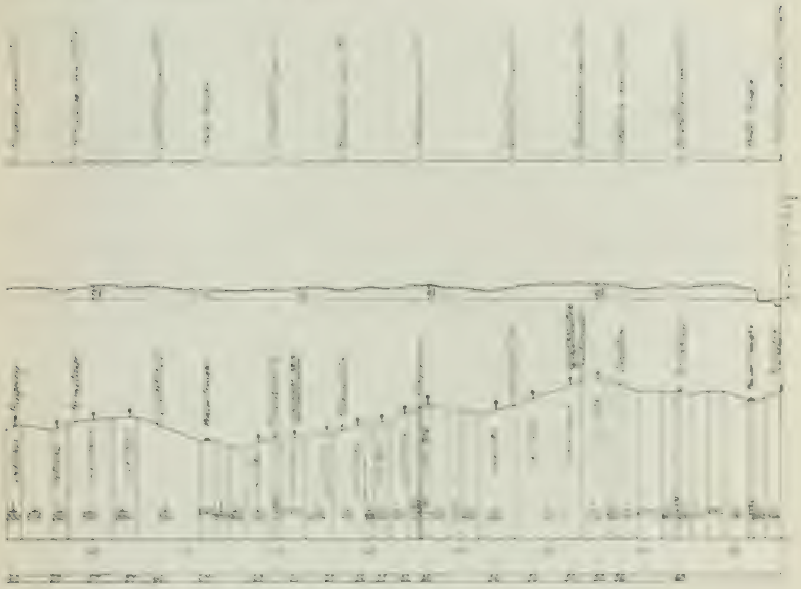
FIG. 54. *Experimental Train, London and*

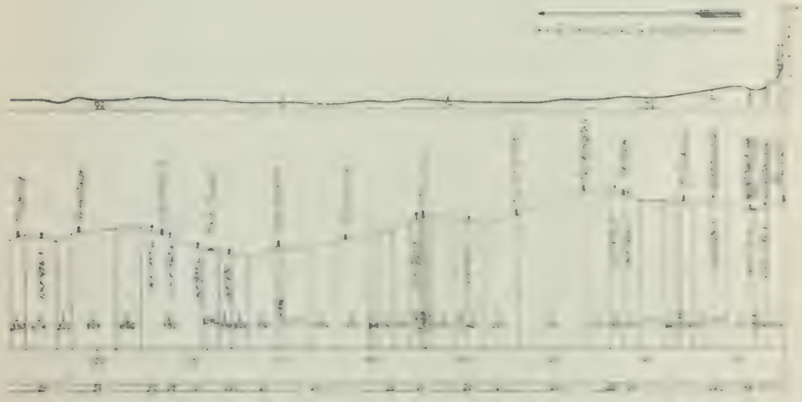
Simple Four-wheels coupled



North Western Railway, 27 *March* 1904.

Engine "Precursor," No. 513.



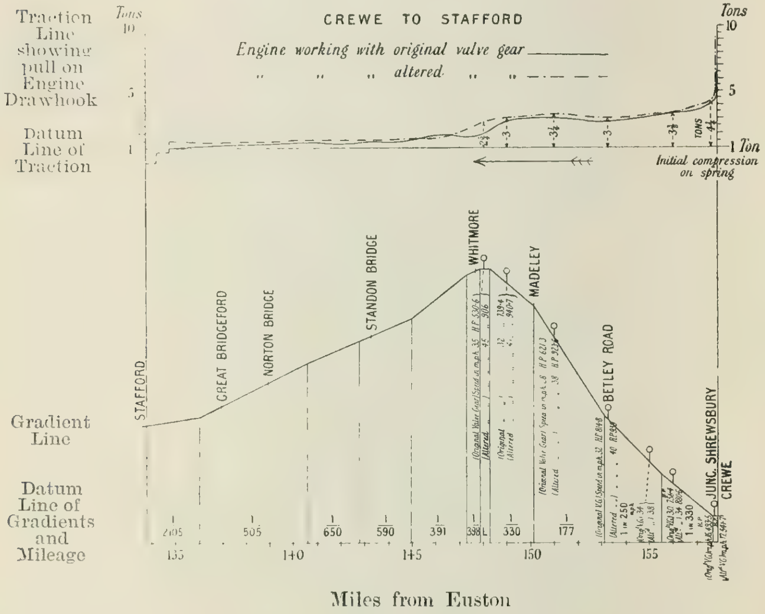


(Mr. George Whale.)

Fig 55.—*Experimental Trips with 4-cyl. Compound*
Comparison of Methods of

In the first two trips—Crewe to Stafford and Stafford to Crewe—the L.P. and H.P. Valves were notched up simultaneously, and the Regulator Valve only partially opened.

In the 3rd and 4th trips the engine was worked with the L.P. Valves in full gear, and the H.P. Valves notched up independently of the low, as required. The Regulator being full open.



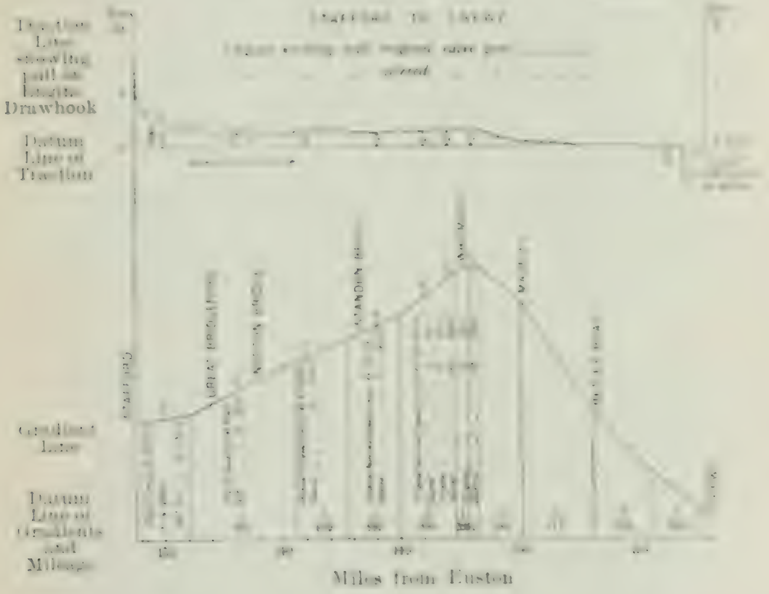
—	Time running from Crewe to Whitmore.	Highest Speed up bank between Crewe and Whitmore.	Time running from Crewe to Stafford.	Maximum H.P.
Original Valve Gear	22 mins. = 28·64 m.p.h.	34 m.p.h.	38½ mins. = 37·79 m.p.h.	814·8 H.P.
Altered Valve Gear	18½ mins. = 34·05 m.p.h.	40 m.p.h.	38 mins. = 44·09 m.p.h.	940·7 H.P.

Engine, L. & N. W. Ry., 27 September 1903. working L.P. Cylinders.

ENGINE "BENBOW" No. 1952.

7' 0" Four Wheels Coupled 4 Cyl. Comp. Express Passenger Locomotive.

	T.	C.	Q.
Engine and Tender	[illegible]	[illegible]	[illegible]
Dynamometer Car	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	123	0	0
[illegible]	[illegible]	[illegible]	[illegible]
Total Weight Inclusive of Engine and Tender	[illegible]	[illegible]	[illegible]
Exclusive	[illegible]	0	[illegible]



—	Time Occupied from Stafford to Whitmore	Highest Speed on bank between Stafford and Whitmore	Time running from Stafford to Crewe	Maximum H.P.
Original Valve Gear	[illegible] = [illegible] m.p.h.	[illegible] m.p.h.	[illegible] mins. = [illegible] m.p.h.	[illegible]
Altered Valve Gear	[illegible] mins. = [illegible] m.p.h.	[illegible] m.p.h.	[illegible] mins. = [illegible] m.p.h.	[illegible]

(Mr. George Whale.)

19 inches diameter by 26 inches stroke. The mean diameter of the boiler barrel was 5 feet $\frac{3}{4}$ inch, and working pressure 175 lbs. per square inch. The total heating surface was 2,009·7 square feet—1,848·4 square feet being obtained from the tubes, and 161·3 square feet from the fire-box. The engine weighed, in working order, 59 tons 15 cwts., of which 19 tons were on each pair of coupled wheels.

An experimental run, to test the engine, was made between Crewe and Rugby and Rugby and Crewe, full particulars of which, and the results, were given in Fig. 54 (pages 424–425). The records shown were automatically taken with the dynamometer car, which registered the speed of the train and the varying pulls on the tender draw-bar. The weight of the train, exclusive of engine and tender, was 374 tons 14 cwts. 3 qrs., the total load being 471 tons 9 cwts. 3 qrs. Some indicator diagrams, Fig. 53 (page 423) were also taken at certain points marked on the sheets, the highest recorded horse-power developed being nearly 1,200. On Fig. 55 (pages 426–427) are shown full particulars and results of experimental trips between Crewe and Stafford with a 4-cylinder compound engine on 27 September 1903, showing a comparison of two methods of working low-pressure cylinders.

Mr. Vaughan Pendred said it would be recollected that at the last meeting he asked how far the external characteristics of a locomotive affected the power of pulling at high speeds, and what effect the diameter of the driving wheels had in the same direction (page 405). That matter had been partly dealt with that evening by Mr. Ivatt, who had given some very interesting information. But it seemed to him (Mr. Pendred) that in order to arrive at anything like a just idea of what took place it would be well to find out, in the first instance, what was the power actually required to drive the locomotive by itself. A great many experiments had been carried out, like those, for example, which Mr. Whale had conducted, giving the draw-bar pull and the engine indicated power, so that one could arrive at a conclusion what the loss was. But none of those experiments had been carried out at very high speeds, for the simple reason that, so far as his experience went—and he thought there were other people in the room who would endorse it—very high speeds were never attained unless the engine and tender were running down hill. On the level, speeds of over 60 miles an hour, unless the engine had got impetus from previously running down hill, were seldom attained. He had endeavoured to obtain, for the information of the meeting, particulars of experiments made at very high speeds. Mr. Drummond had said that though he had not got the facts, he would get them for him. Mr. Drummond had carried out a series of experiments within limits, the results of which were shown in Figs. 56 and 57 (pages 430-433). Speeds of 72 miles an hour were attained. The startling fact to most engineers was that to run an engine and tender alone at those speeds on a level took as much as 800 to 900 H.P. In dealing with these figures, Mr. Sisterson, who carried out the experiments, would explain the conditions under which they were obtained. He (Mr. Pendred) thought it very necessary to say at that point that these figures must not be taken as final. It could be seen that the experiments were very limited in their range, as they must be under the conditions, and he did not think he could do better than read a letter which he had received from Mr. Drummond on the subject: "I send you a second test at different speeds with a light engine. They are not at all satisfactory to me, as we have not sufficient length of dead level line to get these speeds as accurate as they ought to be. The distance we have to run for these trials is only 3 miles with bad curves when entering to the level portion of a line. They may be sufficient to meet your requirements, but they are not sufficiently accurate to form a reliable basis." He (Mr. Pendred) thought it would be agreed that they were valuable so far as they went, but not beyond that point. The interesting point was that there was a 6-foot 10¾-inch wheel—the tyres pretty well worn—and a 6-foot 5[illegible]-inch driving wheel. On looking at the curves, Fig. 58 (page 433), it would be found that they practically bore out Mr. Ivatt's curve, that is, there was a critical point which depended on, and could be regulated by, the type of engine, and in the present case possibly also by the size of the driving wheels. It would be seen that between 60 and 65 miles an hour the lines crossed. Before that, in the early stages of

(*Continued on page* 434.)

(Mr. Vaughan Pendred.)

Fig. 56. *Test of L. & S. W. Ry. Engine No. 706. Running Light.*

Cyls. $18\frac{1}{2}''$ × 26″ *stroke. Diam. of Driving Wheels* $6'\ 5\frac{3}{8}''$.

Weight of Engine and Tender, 90 tons. (Approx.)

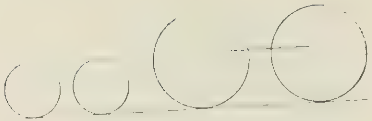
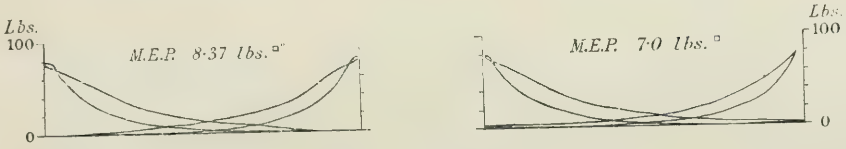


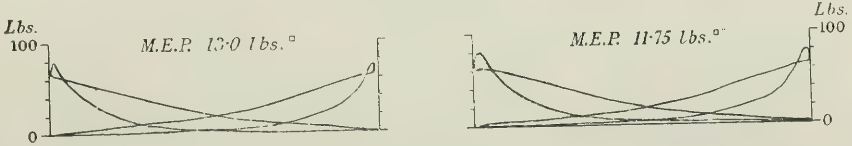
Diagram No. 1.

Left-Hand Cylinder. Right-Hand Cylinder.



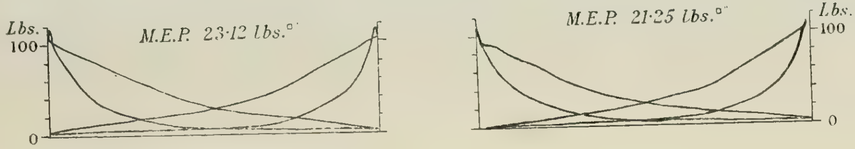
Gauge Pressure	175 lbs. per sq. in.
Cut-off	Mid Gear.
Regulator	Just open.
Speed, miles per hour	28·5.
I.H.P. developed	66.
Tractive Force per ton	9·6 lbs.
Total Tractive Force	869 „

Diagram No. 2



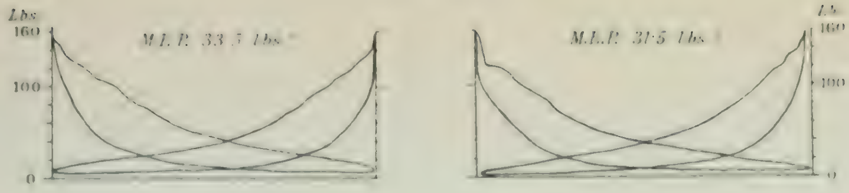
Gauge Pressure	175 lbs. per sq. in.
Cut-off	17%.
Regulator	Quarter open.
Speed, miles per hour	45.
I.H.P. developed	168.
Tractive Force per ton	15·5 lbs.
Total Tractive Force	1400 „

Diagram No. 3.



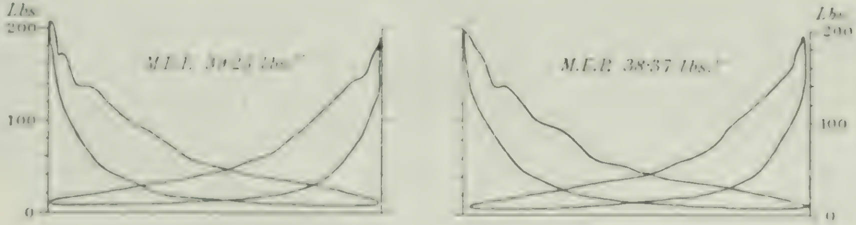
Gauge Pressure	175 lbs. per sq. in.
Cut-off	15%.
Regulator	$\frac{3}{8}$ open.
Speed, miles per hour	55.
I.H.P. developed	370.
Tractive Force per ton	28 lbs.
Total Tractive Force	2523 „

DIAGRAM No. 4.



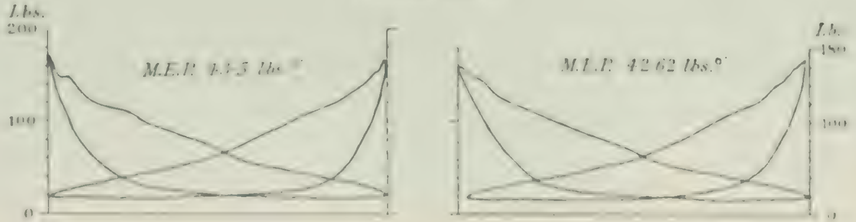
Gauge Pressure . .	[illegible] lbs. per sq. in.
Cut-off	[illegible]
Regulator . .	Half open.
Speed, miles per hour.	[illegible]
I.H.P. developed . .	[illegible]
Tractive Force per ton	[illegible] lbs.
Total Tractive Force .	[illegible]

DIAGRAM No. 5.



Gauge Pressure . .	175 lbs. per sq. in.
Cut-off .	[illegible]
Regulator . .	[illegible] open.
Speed, miles per hour.	[illegible]
I.H.P. developed .	[illegible]
Tractive Force per ton	[illegible] lbs.
Total Tractive Force .	[illegible]

DIAGRAM No. 6.

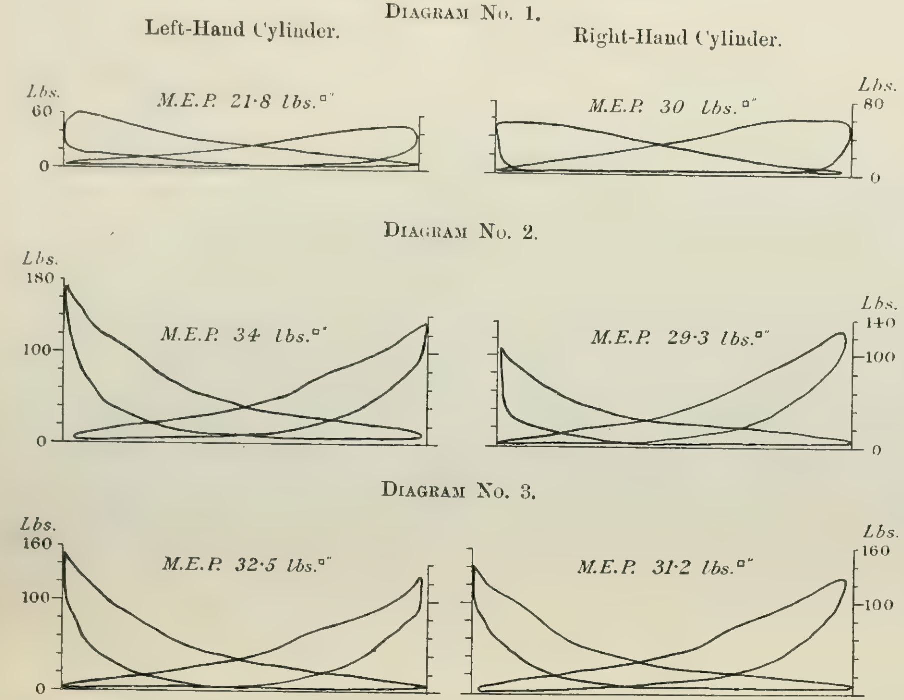


Gauge Pressure . .	[illegible] lbs. per sq. in.
Cut-off	[illegible]
Regulator	Full open.
Speed, miles per hour	[illegible]
I.H.P. developed	[illegible]
Tractive Force per ton .	[illegible] lbs.
Total Tractive Force	[illegible]

(Mr. Vaughan Pendred.)

Fig. 57.—*Test of L. & S. W. Ry. Engine, No. 582. Running Light.*

Cyls. 19″ × 26″ stroke. Diam. of Driving Wheels, 6′ 10¾″.
Weight of Engine and Tender, 80 tons. (Approx.)

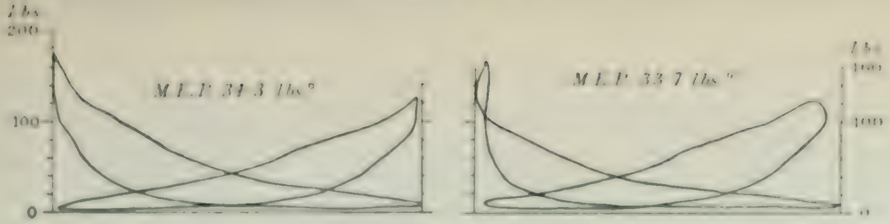


Gauge Pressure	175 lbs. per sq. in.
Cut-off	12%.
Regulator	Half open.
Speed, miles per hour	42.
I.H.P. developed	321.
Tractive Force per ton	36 lbs.
Total Tractive Force	2867 „

Gauge Pressure	175 lbs. per sq. in.
Cut-off	15%.
Regulator	Full open.
Speed, miles per hour	52.
I.H.P. developed	487.
Tractive Force per ton	43·8 lbs.
Total Tractive Force	3512 „

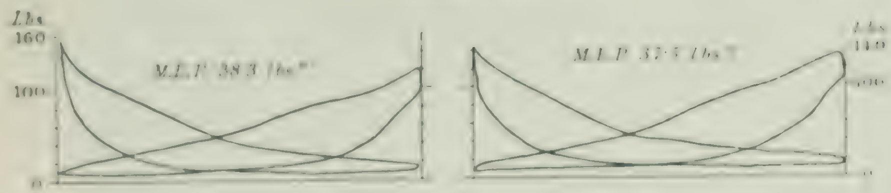
Gauge Pressure	175 lbs. per sq. in.
Cut-off	18%.
Regulator	Full open.
Speed, miles per hour	60.
I.H.P. developed	563.
Tractive Force per ton	44 lbs.
Total Tractive Force	3519 „

DIAGRAM No. 4.



Gauge Pressure	[illegible] lbs. per sq. in.
Cut-off	[illegible]
Regulator	Full open
Speed, miles per hour	[illegible]
I.H.P. developed	[illegible]
Tractive Force per ton	[illegible] lbs.
Total Tractive Force	[illegible]

DIAGRAM No. 5.



Gauge Pressure	[illegible] lbs. per sq. in.
Cut-off	[illegible]
Regulator	Full open
Speed, miles per hour	[illegible]
I.H.P. developed	[illegible]
Tractive Force per ton	[illegible] lbs.
Total Tractive Force	[illegible]

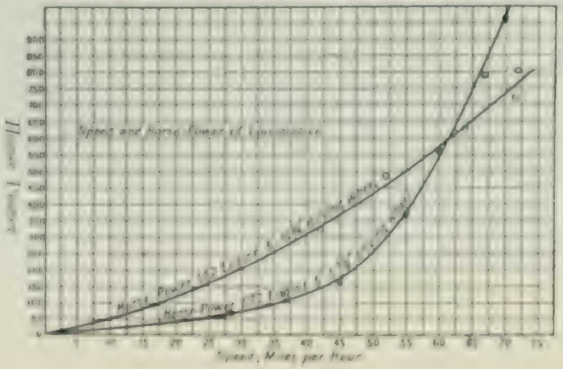


FIG. 8.

Resistance absorbed by light engines running at various speeds.

(See Figs. [illegible])

(Mr. Vaughan Pendred.)

the lower speeds, the small driving wheel had altogether the advantage—it was a freer running engine. But when one got over those speeds it would be found that the small-wheeled engine was at a disadvantage. Mr. Sisterson had plotted out the curve from the different diagrams which were taken, and it would be seen that they agreed wonderfully well with what Mr. Ivatt had given. He thought that as a rule one was very apt to forget, in speaking about the power of an engine, what a very small draw-bar pull represented. It was a very considerable proportion of the power exerted in the case of high speeds. The tractive effort of 5·128 lbs. at 71 miles an hour was a horse-power. If one got anything like 2 tons of tractive effort it meant a very large power. So that with a locomotive the resistance it encountered, even if moderate—it might be air-resistance or other resistance, he could not tell—represented a very high I.H.P. at great speeds. On working out one of the diagrams sent by Mr. Whale, taking one of them haphazard, at 60 miles an hour, the locomotive was using 444 H.P. out of the 1,170 which was used up by the train, taking the weight of the train and the weight of the engine together. It was seen that the resistance of the engine was enormously greater per ton than the resistance of the train. Why was that? He did not know, and he had never met with anybody who could tell him. Here then was a subject for investigation. The Italian Engineers maintained it was head-resistance or air-resistance, and they put in front of the engines cut-airs, and modified the leading end of the engine, with, as they said, good results. But it seemed to him that for the very high speeds now being obtained, with the very long trains, there was a new departure in locomotive practice; and it was desirable that some enquiry should be carried out in order to ascertain definitely what would lessen that large element of resistance, and to find out whence the resistance came, whether from the air, or from the machinery, or from both.

Mr. G. R. **Sisterson** said that, when Mr. Drummond undertook to make the experiments, he was aware at the time that on the London and South Western Railway there was scarcely a suitable portion of the line upon which such experiments could be made. It was necessary that there should be a long stretch of level road, but it happened that in no part of the line was there a stretch of level longer than about 2½ miles. These experiments were made on a portion of level line terminating in a dead end, running down a slight grade, and commencing on the level with a curve. Considerable power was expended in driving the locomotive round the curve, and steam could not be kept on very long or the engine would have been through the buffer stops. The result was that he could not say acceleration had been avoided. A peaked speed-indicator diagram was obtained; but though every care was taken to get the indicator diagram on the peak, he could not be absolutely certain that it was obtained there. That, therefore, to a certain extent spoiled the reliability of the tests.

The diagrams, Fig. 56 (pages 430–431), were obtained from engine No. 706, and he thought they would be found interesting. Commencing with slow speeds, they showed how the height of the diagram varied with the speed, and also how the back-pressure varied with the speed. At the highest speed there was a very sharp hard blast, and there was an irregular pounding action of the pistons in the cylinders. That was always noticeable in an engine working with a long cut-off at high speed. Part of that action was due to the high back-pressure, but only part of it. The rest he thought was due to the reciprocating parts. For instance, at 70 miles an hour, 300 revolutions per minute, it took at the commencement of the stroke something like 80 lbs. pressure to give the parts their proper acceleration, and the acceleration amounted to something near 1,000 foot-seconds per second. It would be seen that actions like that would have a considerable effect upon the piston, consequently one required in the front part of the diagram a great height, and at the finish of the diagram nothing at all, because the work done on the reciprocating parts was of course given out at the last part of the stroke. Hence it would be seen that it was absolutely necessary to have short cut-offs for high speed and a great height in the diagram. Taking the last diagram but one, one got a turning movement as nearly regular as it was possible to obtain from any engine, and that ensured the high speed.

(Mr. G. R. Sisterson.)

The discussion had reference to compound engines, and the question was, what was the connection which his remarks had with compound running; in other words, what was the chief characteristic of compound running at high speed? This was the long cut-off, and his experience was that there was an irregular pounding action of the piston going on due to the improper acceleration of the reciprocating parts. The indicator diagram of a compound locomotive had not sufficient height in the early portions. On referring to page 368 of the Paper, it was stated "It must be noticed that short cut-off is not resorted to, especially at high speed." That was because in a compound engine one would not get a reasonable distribution of work in the two cylinders with short cut-off. Consequently it was impossible, with a compound engine, to resort to a short cut-off.

In July 1902 he had had some experience of the running of Midland express engines at Leeds, and he happened to be there when the first compound was put to work, and was able to make some observations as to the efficiency of both classes of engines. The compound engine was taking its turn and doing its work well with the other normal or high-pressure engines. But he always noticed a cut-off of 50 per cent. and a pounding action going on in the cylinders. He could not make out from his own observations that there was any gain or saving by compound engines compared with the normal type. But the grade on which these runs were made was not suitable for a compound engine to show at its best. It was a long up-hill of 50 miles, of 1 in 100 or so, and then a long drop into Carlisle. He could quite understand that those engines would do much better on the southern portion of that line. It was known that the four-cylinder compounds, which were especially the subject of the present Paper, were doing very well indeed, but there was a difference between those compounds and the other compounds; the pressure was much higher—225 lbs. per square inch was rather an excessive pressure, and indeed he might almost say it was a very serious remedy, because one got a higher diagram, and the action of the reciprocating parts was neutralised, due to the increased height which was obtained in the front part of the diagram. Also the wear and tear of the fire-box when working at that pressure, judging by what it was at 175 lbs. pressure, must be very great. The designers of compound engines had not been ignorant of these facts, and they had devised means for getting the cut-off in the high-pressure cylinder as short as possible. They had proposed to admit steam, automatically or otherwise, into the reservoirs, so that some work was done in the low-pressure cylinder, when cut-off was short in the high-pressure cylinder. That, in his opinion, was a bad remedy, because it increased the back-pressure in the high-pressure cylinder. Moreover, it was not compounding at all, and it was bad in practice to turn fresh steam from the boiler into steam which has done a certain amount of work already, and was therefore partially expanded. Consequently, there must be loss there. Another point was, that if one could not get a short cut-off with the compound—and it seemed certain one could not—how could those great variations in power which were demanded of the locomotive be brought about? At one minute the engine was developing 800 H.P., and in another two or three minutes—say, after having climbed the bank—it was desired to link up as short as possible, and only allow sufficient steam to enter the cylinders as to neutralise the friction of the reciprocating parts; gravity did the rest. That could not be done with the compound engine.

Referring to the curve, Fig. 58 (page 433), he had cited reasons why the power on those curves should be high. For instance, the top curve was for the large-wheeled engine, but with the power required was really less than that shown, because the engine had been a long time out of the shops. Some of their electrical friends, on the strength of that, would say that the steam locomotive was an uneconomical machine because it required 912 H.P. to drive the machine alone, and that seemed excessive. But it must be borne in mind that the machine was being driven 72 miles an hour against very rough weather and high winds, and he could not assume that there was a less air-pressure than 40 lbs. per square foot. Allowing for irregularity of contour, he would say that on that locomotive there was a surface of 100 square feet, so that out of 4,800 lbs. of traction 4,000 was accounted for at once in that way. It was stated in the

(Mr. G. R. Sisterson.)

popular press that one electrical H.P. could be developed for an expenditure of 1 lb. of coal, and that the locomotive would take 5 lbs. to develop 1 H.P. That statement, however, was far from being the case. With engine No. 607 they had got down to within a bare fraction of 2 lbs. per H.P., and he had no doubt that on a carefully arranged trial, and by the application of a feed-water heating arrangement devised by Mr. Drummond, one could get down to $1\frac{3}{4}$ lbs. per H.P. The notion that the high-pressure locomotive was an uneconomical machine had arisen no doubt largely from the bad performance of engines fixed on land, working with low pressure, low piston-speeds, and long cut-offs. On the London and South Western Railway there were tank engines doing suburban work at the usual suburban speed, drawing loads equivalent to 18 six-wheel coaches, which had been brought down to a consumption of about 25 lbs. of Welsh coal per mile. He regretted very much that, owing to the shortness of time for the trials, and the difficulties of the grades, Mr. Drummond had not had time to thrash the matter out, but perhaps at some future time he might be able to do so.

Mr. C. Rous-Marten said he had had no intention of taking part in the discussion, but it had been suggested to him from several quarters that he might possibly be able to say something that would be interesting about the French compound engines under discussion, inasmuch as he had perhaps had more experience with them in the way of experiments than most people. But before entering into that, he wished to say how much he appreciated the most admirable Paper which M. Sauvage had given to the Institution. He thought that Paper must have conveyed a new light to many in this country as to what was being done abroad. He had seen it written and had heard it said that he was an enthusiast with regard to those French compound engines. It might be that he was so now, but that was entirely owing to what he had seen them do. When he paid a casual visit to France seven years ago, he was, of course, aware that compound engines were working in that country. But he did not know what they were like, or what they were doing, any more than did the majority of engineers in England, as he found when he came back. On an ordinary passenger train from Calais to Paris he found one of those engines taking a train of twenty coaches, and timed faster than any train in Great Britain for the same distance at that period; and when he found that engine gaining 18 minutes during the journey, he could not help recognising that he had come face to face with a class of work which was hitherto very rare, in his experience, if not altogether unknown. He accordingly began a series of observations, which he had carried on at intervals during the seven years which had elapsed since. He was very much indebted to M. Du Bousquet for his assistance. That gentleman had been good enough to afford him the use of a dynamometer car and a staff of able assistants, and with those aids he had been able to make a number of observations, the results of which—at least some of them—had been published from time to time, though many remained unpublished.

In Table 4 (page 337) would be found a record of several journeys made by the train known as the "Nord Express," hauled by the first engine put to work of the "Atlantic" type of the de Glehn and Du Bousquet compounds. The last instance given, which was a run on the 13th October 1900, was that in which a load was taken of 365 French tons—as a matter of fact 365½—and it was almost exactly 360 English tons behind the tender. It would be seen that the journey of 95¼ miles, Paris to St. Quentin, was done in ninety-seven minutes. That agreed, within a few seconds, with his own experiment. But in addition to that, what it did not state was that there was a signal stop, or practically a stop, for the train was hardly moving for nearly half a minute in the station yard of St. Quentin, and two signal checks at an earlier period of the journey. One could not allow less than three minutes for those delays; and if so, the engine took those 360 English tons a distance of over 95 miles in the net time of ninety-four minutes, over a road which had one continuous bank of 13 miles with a gradient of 1 in 200. Up that bank the speed never fell below 52 miles an hour, and after dropping from that point, when a little assistance was gained by admitting high pressure into the low-pressure cylinder,

(Mr. C. Rous-Marten.)

a speed of 57 miles was maintained until the summit was passed. On the downward grade the regulation limit of 120 kilomètres, or 74·6 miles an hour, was strictly adhered to, as it had been in almost all the experiments which he had made.

He had made observations with these "Atlantic" engines on every main line in France; but the larger number had been made on the line which was most accessible from England, namely, the Northern of France; therefore he referred in his remarks principally to that. On the particular occasion of which he spoke, M. Du Bousquet invited him to go over. While there he made what he might term two surprise visits. On one occasion there were 305 tons behind the tender, equal to thirty coaches on the South of England lines, and for 10 miles on the level or really on slightly rising ground, similar to that from London to Didcot on the Great Western, 305 tons were steadily hauled at the regulation speed of 120 kilomètres, or just under 75 miles an hour. That performance he had not seen elsewhere. In the third case there were 309 tons behind the tender, and the 13-mile bank was started at a speed of 100 kilomètres, or 62·1 miles per hour. The bank was climbed at a speed of 62 miles an hour from top to bottom. With a load of 270 tons the Caffier's bank was ascended at a speed which never fell below 53 miles an hour, and was maintained for eight miles, the grade being 1 in 125.

Without entering into more detail, he thought those facts spoke volumes for the capacity of the engines. He fully recognised that it was possible some British engines might be able to do the same thing; some of the new ones ought to be able to do it, but he could not speak of that. He was waiting to see it done, and when it was accomplished no one would be more pleased to mention it. But he thought there were several reasons why the engines designed by M. Du Bousquet on the de Glehn compound system did so well. In the first place, there was the advantage which they enjoyed, in common with all compound engines, of using high-pressure steam a second time at a lower pressure, without exhausting it into the atmosphere with a large amount of work still unused. Secondly, he thought those particular compound engines were able to do that with more advantage, owing to their admirable proportions as regarded the ratio between the high- and the low-pressure cylinders. Thirdly, he regarded it as an advantage that the high- and low-pressure cylinders drove different axles. The low-pressure cylinders were placed inside driving the front coupled wheels, and the high-pressure cylinders outside drove the second pair of coupled wheels. By that means it seemed to him that there was produced less strain on the single axle, and there was a better counter-balancing of the reciprocating parts. The next advantage was the high pressure at which the steam was used, namely, 228 lbs. per square inch. There was also the Walschaerts valve-gear which gave an admirable distribution of steam. Another point was the large size of the boiler which had 2,300 square feet of heating surface. Then there was the power of working either non-compound or semi-compound when advisable. Others were the separate cut-off for the high- and low-pressure cylinders, the facilities provided for ensuring a very quick start, and the angle at which the cranks were set. It was a pleasure to him to remember that the engines under discussion were designed by a gentleman who was a fellow-countryman and a brother Englishman with themselves.

Mr. HENRY LEA, Member of Council, remarked that Mr. Ivatt made a most interesting statement, namely, that when a driver wished to run long distances and consume during the journey the smallest amount of water, he did not act according to the text books but let his engine out a little and throttled the steam at the regulator. Mr. Sisterson, he understood, said that it required 80 lbs. per square inch on the piston to produce the acceleration of the reciprocating parts at one of those high speeds. He, Mr. Lea, thought that statement was very likely correct. He suggested that those two statements were quite consistent and explained matters. If 80 lbs. per square inch was sufficient at the turn of the stroke to produce the acceleration, all the pressure above 80 lbs. was simply engaged in loading up the bearings at the turn of the stroke, at a time when the piston was doing no useful work and thereby causing a frictional load upon an engine, that load discounting the draw-bar

(Mr. Henry Lea.)

pull. So that if the boiler pressure was 175 lbs. per square inch, and one linked up and put the regulator wide open until the pressure was 170 lbs., while 80 lbs. was sufficient for the acceleration, 90 lbs. on the square inch was engaged in doing nothing but wasting power. If that were so, it was easy to see why the driver throttled the regulator and let the engine out a bit. In doing so he probably was actuated by his experience, and carried out the process until the initial pressure on the piston was reduced to 80 or 90 lbs. per square inch. The driver thereby got rid of the whole of the waste load upon the large crank-axle bearings and upon the crank-pin; and it was possible to imagine that the gain from doing that compensated, or more than compensated, for the loss of the extra benefit which was supposed to accrue from running at the highest possible degree of expansion by means of an early cut-off.

Mr. **Druitt Halpin** remarked that the author referred to play in the valve spindles (page 363); but it was not at all clear to him (Mr. Halpin) what arrangement that was and whether there were loose valves. He could hardly think that could be possible at speeds such as were under discussion, a speed of 250 to 300 revolutions per minute. Another question was how the heating surface was measured on the Continent, whether it was the practice to measure the ribs or whether they measured the tubes alone. The author gave some details of the Walschaerts valve-gear (page 367) which was very largely used on the Continent, working with one eccentric, the other motion being obtained from the cross-head on the same side. There was a very elegant modification of that gear, which was also used on the Continent and was illustrated in "Engineering" a good many years ago.* But there were a number of those engines, eight-coupled, built for going up a heavy bank at Liège. These were designed by Mr. Stevant, who was one of the chief engineers. In the Walschaerts valve-gear one eccentric was at right angles to the crank, so that being at right angles it did not matter whether it was leading or following the crank, and advantage was taken of this fact;

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* "Engineering," vol. 4, 1867, 12 July, page 33.

and instead of putting on a separate eccentric, he drove from the cross-head of the other side and carried a shaft across the engine, and the link was at the end of the shaft. By that means he obtained both his motions in an elegant way, and without any of the sliding friction due to an eccentric.

The author mentioned that "some contrivances are necessary to avoid excessive compression in compound locomotives" (page 368). The author then went on to say "a much larger clearance than usual must be resorted to." Engineers had not hitherto, so far as he knew, looked upon clearance as any particular blessing, and he did not suppose engineers did so in the present case. He thought that very large clearance must to a large extent have arisen from their own necessities. The trouble of first getting steam into the cylinders, and secondly—which was worse still—getting it out of the cylinders, was great; and he was almost confirmed in that by what he saw that day. M. Sauvage was kind enough to show him another set of diagrams which he had brought over, at remarkably high speeds, at about 60 miles an hour, and he had never seen anything like them before. They were like the diagram shown by Mr. Ivatt (page 419)—a dead straight admission line and then an expansion curve. If they could produce a diagram of that kind with the admission held up in that way the ports must be abnormal, perhaps one-tenth or even one-eighth of the cylinder area. That would, of course, to a very large extent account for their clearance, which was made up of the distance between the pistons and cylinder-cover as one part of the volume, and the port area into its length as the other part of the volume.

He agreed with the author's statement about the great necessity of suitable sized steam-pipes. There was no use in getting enormous pressures of 200 lbs. and upwards, and then losing anything up to 20 per cent. by throttling down, due largely to the steam-pipe. He thought steam-pipes should be large, but then one got into difficulties, because most of the time those steam-pipes were working in the reverse condition to all other steam-pipes, namely, in compression. If they were made of large volume, they were decreasing the already very small steam space in the boiler. But that, like all other questions, must be a matter of compromise.

(Mr. Druitt Halpin.)

The author referred (page 370) to a system of cranks, and also on the same page to the use of superheating. Those who were interested in either of those points would find a complete handling of the matter in some of the last numbers of the Proceedings of the Society of German Engineers. In many of the engines under discussion he noticed that, possibly on account of the weight of the pistons, the tail-rods had been carried through the front of the leading end of the cylinders in the hope of saving the cylinder and supporting the piston. But he never could see the use of that arrangement, unless one got a good cross-head outside and something to carry the weight. The area obtained on the stuffing-boxes was exceedingly restricted and was of very varying nature, because one part of it was partly yielding packing, and he thought it was very much like what the late Mr. Aveling called an "atmospheric bearing" unless one had a good cross-head outside it.

Mr. Robinson referred (page 399) to the length of the grate. On the scale drawing, Fig. 11, Plate 53, they were 9 feet 3 inches long. He very much doubted the advantage of grates of that length, because men could not fire them properly; they could not keep the leading ends of the grates properly filled, and he thought it was very like the striving after the enormous heating surfaces which were common on the Continent forty or fifty years ago. They wanted to get an enormous amount of heating surface, but they got it by leaving clearances of as little as three-eighths of an inch, something which was shown by experience to be impossible. When a number of those tubes were taken out and a smaller heating surface obtained and a better clearance, very much better results were forthcoming.

Mr. Sisterson spoke of fuel consumption in locomotives, and said that it was about 2 lbs. per I.H.P. per hour. He could well believe that, for 2 lbs. to $2\frac{1}{4}$ lbs. for well-maintained locomotives was not at all unusual. He (Mr. Halpin) believed the locomotive to be one of the most economical engines which man had ever made, if it was not the most economical, for it had to be borne in mind what the $2\frac{1}{4}$ lbs. of coal represented. It represented taking hold of a crank-pin and driving it, and that had the most direct connection with its own work (which was the rail underneath) of most classes of machines. If electrical engineers thought they were driving with 2 lbs., or anything else which they liked to name, and took into account all their losses until they obtained their draw-bar pull, they would find it would come out at a very much higher figure.

M. Sauvage, in replying to the discussion, desired, in the first place, to express his hearty thanks for the manner in which his Paper had been received, and for the numerous compliments of which he had been the recipient. He had been much touched by that kind reception, and it had been a great pleasure to him to be present at that meeting.

Mr. Robinson (page 399) had referred to the diameter of the wheels of the engines, and observed that the engines under discussion had wheels somewhat smaller for express traffic than those in England, the diameter of the wheels of such engines in France being about 2 mètres (6 feet 6 inches), while in England the diameters were a little more. The difference was not great, and the question was whether there was room to put very big wheels such as were formerly used for express locomotives. The barrel of the boiler had been raised so as to come above the wheels; and if it were desired to have equally big wheels again, the diameter of boiler would have to be restricted, and that would be an inconvenience. Moreover, the weight of the wheel itself increased with its diameter, and that weight was not suspended. For that reason he believed that the 6-foot 6-inch wheels, though perhaps a little small from some points of view, could not be largely increased with advantage. It must also be remembered, when speaking of fast trains that, after all, the maximum speeds of former years had not been much increased. What had been improved upon was the speed on the level, and particularly in going up banks, resulting in a very definite increased average. The downhill speeds now accomplished were but little in advance of those of a former day. From those considerations there seemed to be no essential reason for increasing largely the diameter of the wheels, and if it were desirable it would be difficult to accomplish.

(M. Sauvage.)

An important point raised by Mr. Robinson—which was also referred to by Mr. Druitt Halpin—was the length of the grate which was supposed to cause difficulties in stoking. Some of the grates in the engines under consideration were over 3 mètres long (9 feet 6 inches). That length of grate might at first appear to be a defect, but it must not be forgotten that those grates were not horizontal but sloped downwards from the footplate, so that it was not difficult for the fireman to throw the coal from the door to the end of the grate. Moreover, coal deposited close to the furnace door ran down towards the far end of the grate, owing to that slope and the shaking caused by the working of the engine. It was something like the ski jumping in Norway; the men jumped very long distances because the jump took place on sloping ground over which they glided at a great speed. A few days ago he was watching a fireman on one of the "Atlantic" engines attached to the Paris-Orléans express. The train was heavy and the speed good, and the man shovelled on about 200 lbs. of coal every four minutes; he did not appear to have much difficulty nor to get particularly tired. Such work could not last very long; no stoker had to do it more than three or four hours at a stretch, and the firing could be done under good conditions.

Mr. Robinson had also asked whether any trouble was experienced on account of leaky tubes. He, M. Sauvage, could say that, as far as he knew, there had never been any trouble from leaky tubes; on the contrary, some improvement seemed to result from the use of the Serve tubes in those particular boilers. That might be due only to the fact that there were fewer tubes, eighty to ninety, replacing about 200 of the ordinary sort: if there was one case of leaky tube in fifty, the total leakages would be less than in the ordinary system. But one remarkable point was worth mentioning, that the men liked the new tubes, not on theoretical grounds, but because they found them more easy to keep in order. The men in the locomotive sheds also preferred them. For his own part, he had been a little surprised to learn that, because he thought those tubes, being stiffer and hotter than the ordinary tubes, would expand a little more. The temperature of the tube was higher than that of the ordinary tube, because the quantity of metal in it was greater and the ribs were heated at a higher temperature, and he thought that on this account they would be more likely to glide through the holes. But that action was not experienced; indeed the cases of leakage were very few.

With regard to Mr. Halpin's question (page 442) as to what was the usual way of measuring the heating surface, diverse views were at first expressed on the subject, but recently French locomotive superintendents agreed to adopt precise rules so as to make fair comparisons. The practice now was to take the whole surface in contact with the hot gases, so that it included the projecting parts inside the tube.

Mr. Churchward had spoken about the comparison of the four-cylinder compounds running on the Great Western Railway and the very powerful and fine simple engines built to work the same services. The boiler pressure was about the same. If he understood rightly, the boiler pressure first used by Mr. Churchward was 200 lbs. per square inch, and he believed that gentleman intended to raise the pressure to 225 lbs. per square inch, so as to have exactly the same pressure as in the compound. Mr. Churchward's experiments were exceedingly interesting. First, it was proved by them that the same service could be got out of properly-designed simple locomotives with two cylinders as out of the four-cylinder compounds. But the comparison would certainly go further; it would also be seen what was the coal-consumption and what the maximum possible power of the engine. The idea expressed by the French locomotive superintendents was that they wanted more work got out of the same quantity of coal, and that was obtained by the compound system.

The question of costs was one of great interest, and it was to be hoped that the experiments about to be made on the Great Western Railway would help to solve that important problem. A magnificent experimental station had recently been built by Mr. Churchward at the Swindon Works, a station somewhat like—and in some respects it might be better than—the laboratory at Purdue University in America, where locomotives could be tested running on pulleys with brakes, under perfectly known and reliable conditions which

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could be altered one by one. It was certain that the testing of the different locomotives would furnish very useful data. The station built at Swindon for that purpose was the first in Europe, and the Great Western Railway and its able superintendent were to be heartily congratulated on having taken such a step.

Mr. Churchward said that it was very difficult to get a draw-bar pull of 2 tons at a speed of 70 miles an hour, and everyone who had experience of locomotive working would agree with him. Still, with the powerful "Atlantic" locomotive in use on the Paris-Orléans Railway, even higher pulls had been obtained in some cases. Fig. 59 (page 499) showed a portion of a record of the dynamometer car on that railway, and it would be seen that for a long distance the pull was 2⅓ tons, and the speed from 65 to 70 miles an hour. Indicator tests were made at the same time, and the diagrams showed that the indicated horse-power came up to nearly 1,900. The effective power, that on the draw-bar, was in some cases over 1,300 and 1,400. For a length of 13 kilomètres (8 to 9 miles), the draw-bar pull corresponded to nearly 1,000 horse-power. The average speed was 69 to 70 miles per hour, and the main draw-bar pull 2,350 kg., or 2⅓ tons. Those figures were in proportion to what had been done on the Great Western Railway, as the Paris-Orléans locomotive was a little more powerful—it had a larger boiler and larger cylinders—than the one on the Great Western Railway.

The draw-bar pull was the most important point to be considered, as several speakers had observed, and mention had been made in that connection of the possible resistance of the rolling stock in France as compared with that in England. Members were aware that the question had been very fully studied by Mr. Aspinall, who had contributed a most important Paper on the subject.* No doubt in some cases the resistance per ton at a given speed caused by the rolling stock did not appear to be the same, but he thought there was no reason to suppose that, as a whole, the resistance of the French rolling stock would be less than that of the English rolling

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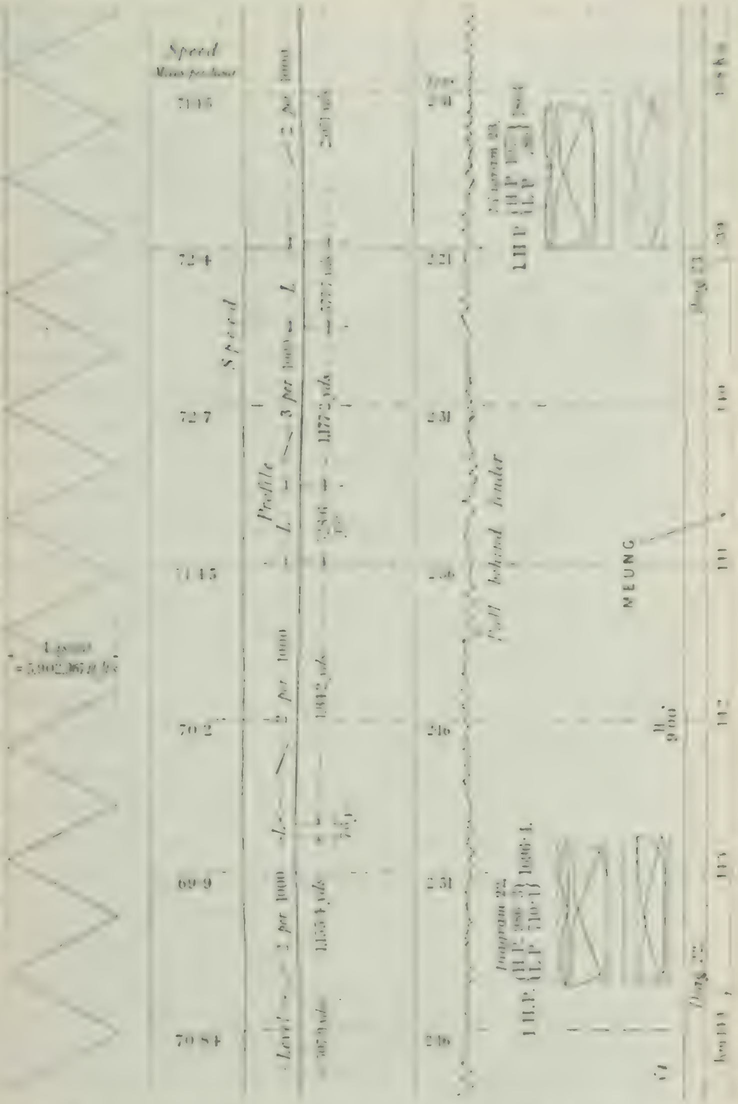
* Proceedings, The Institution of Civil Engineers, 1897–8, vol. cxxxiii page 13.

FIG. 59. *Paris-Orléans Railway. Train F. 5 Dec. 1903. Part of Dynamometer Record.*

(See Revue Générale des Chemins de fer et des Tramways, March 1903, page 183.)



Length of journey considered (from km. 173 to km. 136) 22·9 miles.
Steam Admission: H.P. 55%; L.P. 65%.
Mean Speed 67·9 miles per hour.
Mean pull behind tender, 2·4 tons.
Total work in foot-lbs of the tender hook, [illegible]
Mean power behind tender, [illegible] H.P.
Mean power indicated in the cylinders, 1711·2 H.P.

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stock. Still, when bogie carriages were used, it had been found on the Northern Railway that the resistance was somewhat less than with the old ordinary carriages.

The boiler pressure had been several times mentioned in the discussion, and it was the only source from which trouble or increased expense might come. High pressure was wanted chiefly to make a very powerful and at the same time a very light engine. But if the question of combining lightness and power did not come into consideration, certainly it would be more advisable not to go so high as 200 to 225 lbs. per square inch. It had been found that, with pressures not quite so high, very good economy might be obtained on compound locomotives. For instance, the first compound locomotive used on the Northern Railway, No. 701, which, however, was small compared with those built now, worked at only a pressure of about 185 lbs. per square inch, and was still the most economical engine running. But he thought it was necessary to revert to the very high pressure to get sufficient power out of an engine, which was to be light, and not to exceed certain limit weights.

He thought all engineers were of the same opinion regarding one point which had been touched upon by Mr. de Glehn. He believed that Mr. de Glehn did not quite explain what he wanted to say when he said that, by the use of two cylinders with the pistons exactly opposed to each other, a more regular turning moment could be obtained. Mr. Churchward objected to this, that the turning moment of the four-cylinder engine could not be better than that of the two-cylinder engine. By the use of the opposite cranks, the equilibrium of the reciprocating motion was obtained without counter-weights; it was well known that counter-weights used to balance horizontal motion gave rise to a vertical perturbation, causing a continual variation of wheel-pressure on the rail. With counter-weights only for the equilibrium of the revolving parts, the weight on the rail did not vary at all, and the locomotive was not so liable to slip.

The experience of the compounds in France, and especially the experiments on the Paris-Orléans Railway, agreed with what Mr. W. M. Smith said about the working of the three-cylinder compound on the Midland Railway. Mr. Smith (page 405) said the working was equally good with light and with heavy trains; it must be understood that when one referred to light train weights, there was a certain limit below which it would not be reasonable to go. It would not be advisable to use powerful engines to take trains of four or five carriages, but with the ordinary limits of weights of trains it had been found on the Midland Railway, as Mr. Smith had said, that the coal-consumption was economical, whether with light or with heavy trains.

A long series of experiments, made on the Paris-Orléans line with trains of different weights, had shown a steam-consumption per horse-power per hour never differing much from 23 lbs. The horse-power was neither the indicated horse-power, nor the power calculated from the draw-bar pull; but it was the horse-power exerted by the wheel on the rail, and that power was calculated from the results of numerous experiments made with the use of the dynamometer car. The Paris-Orléans Railway engineers were confident that they could calculate carefully and closely the effective pull exerted by the wheel on the rail, and that was what they called effective horse-power. They found that with trains of 220 tons the average steam-consumption was 23 lbs. With trains of 260 tons it was 22·6 lbs. With heavy trains of 352 tons it was 23·7 lbs. There was therefore hardly any difference in the water-consumption per effective horse-power per hour in all these different cases. When one came to practical work it would be seen that heavy train working was more economical than light train working. It was most definitely so, because the weight of the engine was a smaller proportion of the weight of the whole train.

Very minute and interesting remarks on the subject of the possible variations of speed when indicator diagrams were taken had been made by Mr. J. W. Smith (page 412), especially with regard to the diagrams taken on the Northern Railway. As a rule the people who made the experiments tried to get a uniform speed a little before and a little after taking the indicator diagram. There were exhibited copies of records on the Paris-Orléans Railway, a section of which was reproduced on Fig. 59 (page 449), from which it would be seen that the variation of speed was rather small at the time the diagrams were

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taken. Those would be deposited at the Institution, so that it would be possible for members who would like to investigate the question, to see what might be the variation of speed at the time the diagram was taken, and to calculate the effective variation of speed.

Mr. Smith made a very correct observation, when he said that in France a large improvement in the train service had taken place of late years. At the same time the compound engines were introduced to work that improved service. But it was not quite sound logic to say that therefore the improvement of the service was due to the use of compound locomotives. The two facts came together, but that was not a proof that one was a consequence of the other. Certainly the improvement in the French express service was due to many causes; first of all, to the need for improvement. When people wanted to do something they tried hard to do it, and generally they got what they wanted. The improvement in the rolling stock, the introduction of bogie carriages, the improvement in the permanent way and of the signal system, &c., came into play, but it was reasonable to suppose that the improvement in locomotives in France had much to do with those other improvements, and it seemed certain that if the new stock of compound locomotives had not been introduced, it would not have been possible to improve the speed of the express trains with their extra weights. As a matter of fact, however, both had been improved at the same time. A remark had been made by Mr. J. W. Smith (page 413), and also by another speaker, about a little defect in the four-cylinder compounds, namely, the outside pipes. The pipes ran from the top of the boiler to the high-pressure cylinder, and from the high-pressure to the low-pressure cylinder; that second pipe was very short indeed and well protected under the plates. Still, there was a certain surface of outside pipe exposed to the cold. Naturally those pipes were covered as carefully as possible with non-conducting materials, and he believed the loss of heat was not very large. At the same time, if one studied this question minutely, it might be observed that in the three-cylinder compounds in Switzerland, and he believed also on the Midland Railway, there was a small part of the receiver which was in contact with the high-pressure cylinder, and there was only the thickness of the cast iron—a little more than 1 inch—between the inside of the high-pressure cylinder and the receiver. The transfer of heat from the inside of the cylinder to the receiver would result in some loss. If one wanted to have the most perfect conditions possible, the exhaust steam must be taken from one cylinder quite away from that cylinder. But it might be said that all these cases were of small practical importance.

Mr. Ivatt was kind enough to compliment him on the conversion of metric measures into English dimensions. The compliment was not due to him, but to the Secretary and staff of the Institution, who did that difficult work for him.

An important point had been raised by Mr. Sisterson about the working of steam in cylinders (page 436), and that gentleman said it was very important to have a short cut-off at high speed, because a diagram with high pressure and short cut-off, when one considered the inertia tracing showing the effect of the acceleration of the piston, and when one took into consideration that high inertia action, would give a very regular turning moment. He believed that if that same tracing were made with the diagrams of the compound engine, that is, a full diagram with high pressure at the beginning combined with the inertia line, it would be found that the force on the piston was sufficiently regular too.

It had been said that the compound did not seem designed to give economically great variations of power, as the cut-off was always long when a light draw-bar pull only was required; but a short cut-off might be resorted to, and was resorted to, in the high-pressure cylinders; then the receiver pressure dropped to almost nothing. In those cases, for instance, when running down a gradient at high speed with a very small pull, the diagram of the low-pressure cylinder came to very little indeed. He did not see that there was any difficulty in keeping short cut-offs, from 20 to 30 instead of 50 to 60 in the high-pressure cylinders with four-cylinder compounds.

Mr. Halpin asked a question about the valve spindle (page 442) applied to tandem compound engines with two valves used on the Ceinture Railway. The valves of the high- and low-pressure cylinders were worked by only one spindle, and in the middle of the

(M. Sauvage.)

spindle, between the two valves, there was a play of about $\frac{1}{4}$ inch, so that the low-pressure valve, which was in front, was always a little behind the high-pressure one; that gave a later cut-off and less compression. Mr. Halpin said he thought that would not work well at high speeds, but it must not be forgotten that those engines were tank engines working suburban services.

With regard to the clearance in the cylinders, it had been found that a large clearance was necessary. In the first compound the clearance was too small, causing excessive compression. It had been increased, and at the same time the steam passage had been enlarged. On the Eastern Railway of France they used piston-valves, with considerable advantage; in experiments made on that railway on similar locomotives, with the only difference of piston against flat valves, an economy of nearly 10 per cent. of coal had been observed, due to reduced wire-drawing and compression of steam.

With regard to tail-rods, they were largely used on French locomotives, and even in England also. When not used, especially with large cylinders, cases of broken rings were frequent, and it had been found in France that by the addition of tail-rods the piston-rings lasted much better. They prevented lateral motion, such as when the piston was supported only from one side; and there was a tendency to use those tail-rods not only for the low-pressure cylinder, which was large, but also for the high-pressure cylinder. Engineers in the running-shed department were all in favour of tail-rods, although they seemed to necessitate a little more trouble to keep in order. They however saved a great deal of trouble with broken rings.

He desired to mention a new compound which had been introduced on the Ceinture Railway of Paris. It was a large tank-engine weighing 80 tons, and had eight-coupled wheels and a bogie in front. It had large water-tanks and large coal-bunkers, and was said to be working very well. It was a very recent addition to the list of four-cylinder compound locomotives used in France.

The PRESIDENT said he had already, on behalf of the Institution, thanked the author for his valuable Paper, and it only remained for him to add to that an expression of his admiration of the way in which he had answered the whole of the discussion that had taken place on it. It had been a very great treat to listen to M. Sauvage's exhaustive reply.

The present was the last meeting of the session. The next meeting would be on May 31st, at Chicago, and he hoped that those who intended going would speedily book berths and notify the Secretary of their intention. The Secretary had prepared a complete detailed programme, which was only waiting for one event to be settled before being issued, namely, a Reception at the British Pavilion in the St. Louis Exhibition grounds. In addition, there would be a Meeting in London at the end of July, when an election of new Members would take place, and a Paper would be read and discussed. A Conversazione would also be held.

Communications.

Mr. SAMUEL W. JOHNSON, Past-President, wrote that he had read with much interest and pleasure the Paper by M. Sauvage describing the progress of Compound Locomotive Engines in France, particularly the four-cylinder compounds recently made, which had proved generally more satisfactory than the simple engine. He was glad to have this opportunity of stating his experience with the three-cylinder compounds designed for the Midland Railway.

Up to within the last few years the requirements of the traffic on that railway did not necessitate the building of engines of such great power as the largest four-cylinder express compounds of the new "Atlantic" type built for the Paris-Orleans Railway and described on Table 2 (page 333) working with the high boiler pressure of 228 lbs. per square inch. Previous to the introduction of larger coaches, heavier trains and accelerated time-bill services,

(Mr. Samuel W. Johnson.)

ordinary four-wheels coupled express passenger engines, with a four-wheeled bogie in front, were used, with boiler pressures advancing from 140 to 160 and 180 lbs. per square inch, and they proved both effectual and economical. The rise from 140 to 160 lbs. boiler pressure showed at once an average reduction of fuel of about 4 lbs. per mile on the Nottingham and Leicester to London traffic, and this economy was apparently maintained on the rise of pressure to 180 lbs., although not actually definable owing to increased weight of trains and accelerated speeds.

From experiments made with a simple four-wheel coupled passenger engine by Mr. Drummond on the Caledonian Railway in 1889 with a boiler-pressure up to 200 lbs. per square inch, he came to the conclusion that the most economical results as regards coal and water-consumption were obtained in simple engines, when the pressure did not exceed about 175 lbs. per square inch. Bearing this in mind in designing a more powerful express engine for the Midland Railway in 1900, it was obvious that to take full advantage of the benefits of higher pressure a greater range for expansion was necessary, and this was available only by compounding. Having noted carefully the working of compound engines as introduced on the London and North Western Railway and the North Eastern Railway in this country, and also those in France and America, the system which commended itself as being most elastic to meet the varying conditions of both light and heavy working with economy was the three-cylinder Smith's compound as tried on the North Eastern Railway.

By the introduction of an extra cylinder and valve gear and an increase of boiler pressure up to 195–200 lbs. per square inch, an increase of power over the simple engine of 35 per cent. has been attained. The additional high-pressure cylinder and gear, connected to a central crank on the driving axle intermediate between the two low-pressure cylinders, was a simple arrangement, and the adjacent position of the cylinders with their steam-pipes and steam-chests in common, arranged in line under the smoke-box, offered the minimum amount of surface for friction and for condensation; and by the special starting and regulating valve the engine could be worked either as a compound or a semi-compound, and was thus adapted for light or heavy loads. The steam-pipes coming from within the boiler and passing through the smoke-box direct delivered superheated steam to the steam-chests.

By this three-cylinder arrangement the following advantages were obtained, namely, ample starting power by the automatic regulating valve, and by two of the cranks always being operative; small first cost, fewer detailed parts, and less friction, and consequent economy in both oil and coal. In the four-cylinder engine the division of power through two axles and the balancing of the reciprocating parts as set forth by M. Sauvage were desirable advantages, but these were of necessity accompanied by outside steam-pipes from the boiler to the high-pressure cylinders, and again from them to the low-pressure cylinders. The adhesive weight of 36 tons appeared to be light for such a powerful engine, but M. Sauvage stated it was expected this weight would be increased to 40 tons. How far the three-cylinder arrangement with the central crank would admit of further increase in the size of cylinders and higher pressures had yet to be ascertained, but so far no inconvenience had been experienced from the driving of all the power through one axle. The Midland engine under normal conditions of working was about 26 per cent. less powerful than the Paris-Orléans engine; this, however, if an equivalent boiler-pressure were used, would be reduced to 8 per cent. The results obtained by the working of the three-cylinder compounds had been highly satisfactory, both as regards loads taken and economy in working.

The following summary of figures (details of which were published in "Engineering" of 6th February and 23rd March 1903) gave the results of working for one week on one of the heaviest sections of the main line, namely, from Leeds to Carlisle and back. On the outward journey the gradients included 15 miles of 1 in 100 and 5 miles of 1 in 128. The average load behind the tender for the five trips was 250·64 tons, and the average weight of engine and tender was 104·16 tons, making a total of 354·80 tons gross load, run at a speed of 52·48 miles per hour. The consumption of fuel was 45·5 lbs. per mile, and the water

(Mr. Samuel W. Johnson.)

evaporated amounted to 7·3 lbs. per lb. of coal. On the return journeys the average load for seven trips from Carlisle to Leeds, which included gradients of 1 in 100 for 8 miles and 11 miles of 1 in 128, was 152·65 tons behind the tender, and the average weight of the engine and tender was 107·75 tons, making a total of 260·40 tons gross load at a speed of 51·2 miles per hour. The consumption of coal was 25·43 lbs. per mile, and the water evaporated amounted to 9·45 lbs. per lb. of coal.

The following are specimens of heavy trains running between St. Pancras and Leicester by the compound engines:—

Engine	No. 2634.
Date	12 Dec. 1903.
Train	10.15 a.m., St. Pancras to Leicester.
Vehicles	21 (16–17 tons each).
Approximate weight behind tender	370 tons.

Engine	No. 2634.
Date	27 Nov. 1903.
Train	4.20 p.m., St. Pancras to Leicester.
Vehicles	19½.
Approximate weight behind tender	330 tons.

Engine	No. 2635.
Date	17 March, 1904.
Train	10.15 a.m., St. Pancras to Leicester.
Vehicles	19.
Approximate weight behind tender	324 tons.

A specimen of detailed working is given on Table 23 (page 459).

No. 2634 ran an average mileage per week of 1,434 miles for five weeks ending 10 March last.

No. 2635 ran an average mileage per week of 1,446 miles for five weeks ending 10 March last.

An extract from the running sheets Leicester–London shows that engine No. 2,635 ran trips amounting to 618 train-miles with a load of approximately 300 tons behind the tender at a mean speed of 53 miles per hour on a coal-consumption of 35·5 lbs. per mile.

[*COPY.*]

TABLE 23.

MIDLAND RAILWAY LOCO. DEPT.
17/3/1904.

Working of Engine No. 2635. *Date*, 17/3/04. *Train*, 10.15 *a.m.* *From London to Leicester.*

Stations.	Times.				Vehicles.		Pressure.			Notch	Regulator open.	Remarks
	Booked.	Actual.	Mins. early.	Mins. late.	Actual.	Equal to.	Boiler.	Controller.	Receiver			
St. Pancras . .	10.15	10.16¼	—	1¼	12	19	195	—	—	—	—	
Kentish Town .	10.19	10.20¼	—	1¼	„	„	195	185	70	10	F	
Hendon . . .	10.25	10.28	—	3	„	„	185	180	65	9	F	
St. Albans . .	10.40	10.43	—	3	„	„	185	180	70	8	F	
Luton . . .	10.51	10.54¼	—	3¼	„	„	190	185	70	8	F	
Bedford . .	11.12	11.12¾	—	¾	„	„	190	—	—	—	—	
„ dep.	11.15	11.16¼	—	1¼	„	„	195	—	—	—	—	
Souldrop . .	11.26	11.28¾	—	2¾	„	„	180	170	65	9	F	
Wellingboro' .	11.34	11.36¼	—	2¼	„	„	170	165	60	8	F	
Kettering . .	11.42	11.43¼	—	1¼	„	„	170	165	60	8	F	
Market Harboro'	11.54	11.56	—	2	„	„	180 }	Shut for curve.				
Leicester . .	12.14	12.12¾	1¼	—	„	„	160 }					

Weather: Fine, some wind.

Driver: J. Bayliss

General Remarks.

Engine ran through all cool.
Engineering check, Cricklewood.
Signal checks, Kempston Road Junction Distance.

(Signed) F. D. M[illegible]

London and Leicester and Nottingham District.

Ruling gradients, London to Leicester
- 15 miles, 1–160 to 1–220.
- 3¼ „ 1–119.
- 3½ „ 1–130 to 167.

It appeared to the writer that this subject was of such importance to railway companies that it was worth their consideration to institute a series of trials of several types of powerful express engines for main-line passenger work, and also trials of heavy main-line engines for goods and mineral work, which should be arranged to be made under such conditions as would ensure accurate results, in ascertaining which engine in each class gave the highest efficiency combined with the highest economy in working a given load at a given speed, and with equal boiler pressures. The results of such trials would, he felt sure, be of the greatest interest to mechanical engineers and to the Boards of railway companies.

M. ANATOLE MALLET wrote that the Institution had perhaps not forgotten that twenty-five years ago he read a Paper * before the Institution on the Compounding of Locomotives, giving the results obtained by him in that way since 1876. The question was quite new at that time, and, so far as could be judged from the discussion that took place, the general impression amongst the members present at the meeting, except Mr. F. W. Webb, was that the subject offered but little probability of definite success. The author, on the contrary, expressed great confidence in the future of the compound locomotive, and results had fully proved that he was right in his expectation. In 1879, there were only a dozen compound locomotives, all of which were of moderate or small size. Their number amounted to-day to more than 18,000, and amongst them were included the largest engines ever built. In Russia, for instance, the ratio of compound already exceeds one-half the total number of locomotives.

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* Proceedings 1879, June, page 328.

Turning now to M. Sauvage's valuable Paper, he was delighted at the success of the four-cylinder locomotive so largely used on French railways. In fact, he believed he was in some measure entitled to flatter himself for having been the first to point out the essential features of that type of engine, namely, the coupling together of axles, one being worked by a pair of high-pressure cylinders, and the other by a pair of low-pressure cylinders. Such an arrangement was described, amongst the different designs by which could be realised the compounding of locomotive engines, in a Paper read in 1877 before the French Society of Civil Engineers.* It was only in 1888–89 that it was put into practice on the French railways, as the first "de Glehn" four-cylinder locomotive, built in 1885, had not the driving-axles coupled together and no balancing effect could be obtained. It was, in some measure, roughly speaking, a Webb compound engine with the low-pressure cylinder divided in two, otherwise not a small improvement as regards the facility of starting and the regularity of the turning moment. At that time the use of four cylinders with distinct working gears was considered as a substitute for coupling-rods, as shown in the early design of the late M. Jules Morandière in 1867, and the patent of Dawes taken out in 1874.

The writer begged to be excused for venturing to think that the above case of foresight had contributed to his having been awarded in 1902, one of the late Mr. H. Schneider's (of Creusot) prizes, by the French Society of Civil Engineers for his Papers on compound locomotives, which prizes, according to the regulations, were awarded for books or papers judged as being the most useful for the development of various industries in France. That reward had the additional merit of having been conferred on the recommendation of M. Du Bousquet.

He did not intend to discuss quick-running engines, in which he did not have much personal experience, as he was working in

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* The writer's priority on that point was proclaimed by M. von Borries in a Paper on "The Development of the Compound Locomotive," presented at the Chicago Meeting, July 1893, of the American Society of Mechanical Engineers, vol. xiv, page 1183.

(M. Anatole Mallet.)

another direction—the slow-speed high tractive power locomotive. He desired to offer a few remarks about some details of the four-cylinder engine, details to which Mr. de Glehn seemed to attach a large degree of importance, namely, the intercepting valve for starting and the independent reversing gear. He was not, he believed, liable to be suspected of prejudice against these features that he was the first to use in two and four-cylinder locomotives; but he considered that if they were highly suitable for two-cylinder compound locomotives, they introduced without any necessity when used in four-cylinder engines an unavoidable complexity, and, what was worse, the possibility of mismanagement on the part of the engine-driver. He himself had, in some cases of emergency, obtained a great advantage in having fitted his first four-cylinder locomotives with a device enabling the two pairs of cylinders to work independently with live steam, but, notwithstanding this, he had for some time given up that design as well as the independent reversing gear. He had at present got nearly 700 four-cylinder compound articulated locomotives for all gauges and of various sizes, from 12 to more than 100 tons, and he set a serious value from the fact that not one of the forty or fifty railroads using these locomotives (and one of which, the Siberian Railway, already owned 120, and others 50, 40, &c., engines, resulting from repeated orders) ever made the slightest complaint about the want of a special starting device or independent reversing gear. The use of a safety-valve loaded to about one-third of the boiler pressure on the receiver, and occasionally of a supply in the same receiver of live steam, the supply regulated by a cock connected for greater simplicity to the reversing gear, was, even in engines running heavy trains at high speeds, quite sufficient for a free starting, as it had been proved from a long and extended practice. On the other hand, if the use of independent reversing gears was claimed to render easier, in some cases, for instance, when running down gradients without steam, the quick moving of engines, the same result could be obtained in a simpler and safer manner from air-valves fitted on the cylinder-covers or valve-cases, or from by-passes between the steam-ports.

He firmly believed that the last word had not yet been said about the improvement of the steam locomotive, and that it was now in the way of three or four-cylinder compound engines using highly superheated steam, with really practical superheater, that progress must be looked for. He wished it to be distinctly understood that the criticism he had expressed about some details of the French engines in question by no means affected the regard and admiration that he entertained for the engineers, who had brought these locomotives to their present high grade of perfection.

Mr. WILLIAM MARRIOTT wrote that he would be glad if the author would kindly amplify his remarks (page 375) with regard to the inconvenience of the use of mild steel. The author's experience entirely accorded with his own, and if he had his own way, he would in many cases go back to the use of iron for boilers, although he was aware that in this he differed from many.

Mr. J. D. TWINBERROW wrote that the principal features of French practice appeared to be the self-balancing of the forces due to the reciprocating parts, the connection of the inside and the outside cylinders to separate axles, the construction of a thorough system of bracing between the frames and the adoption of a simple expedient for passing the high-pressure exhaust directly to the blast-pipe when required. These were points of prime importance, in their effect upon the efficiency of the machine and with regard to convenience in working.

Frames that were not thoroughly well braced by means of deep traverse plates, with the equivalent of horizontal bracing between them, were liable to distortion under working stresses; this involved increased frictional resistance, greater liability to derailment, and a tendency to lateral oscillations at high speed owing to the torsional flexibility of the structure. Continuous footplates riveted along the outside frames and secured to strong outside angle-bars would be efficient as a substitute for horizontal bracing between the traverse members, were it not that they required frequently to be cut away to clear the wheels just at those parts where the staying was most required.

(Mr. J. D. Twinberrow.)

The progress of compounding in this country had been retarded by the bad reputation for starting which the earlier examples acquired. When the non-return valve in the receiver was leaking, and when there was no by-pass for the high-pressure exhaust, an engine which was standing in a bad position for starting was liable to become stalled by the steam accumulating at the back of the high-pressure cylinder. It would be interesting to ascertain if any advantage would result from the practice which the writer suggested many years ago, of balancing not only the reciprocating forces, but also the couples by altering the angles between the cranks. The objection that the periods between the four beats of the exhaust in each revolution would not be equal did not appear to be of any moment; irregularity not only in period but also in intensity of beat was by no means unknown in the case of ordinary locomotives. The forces might be completely balanced in the case of a three-cylinder engine with cranks at 120° apart, and if the effect of the couples was unimportant upon heavy engines with great length of wheel-base, it would appear that this type might possess some features of advantage on the score of greater simplicity, whilst the single inside cylinder imposed little restriction on the length of the crank-axle bearings.

The details of the Walschaerts valve-gear given in the Paper were extremely interesting, as they showed how the difficulty of arranging a well-supported gear, with all the working joints symmetrical with respect to a vertical plane, had been overcome. The oscillating links were of channel section with internal working surfaces as usual in French practice; he would ask the author if flat bar-links of the kind usual in marine engines were ever made use of? They appeared to possess some advantages, and the writer had adopted this type in the design of some small reversing engines which he made some years ago. Fig. 60 (page 465) was a sketch of the arrangement, from which it would also be seen that the valve-spindle guide and attachment were of the same general type as those illustrated in the Paper.

He feared that fire-box troubles were unavoidable in the case of large boilers worked at high pressure; they might be mitigated but

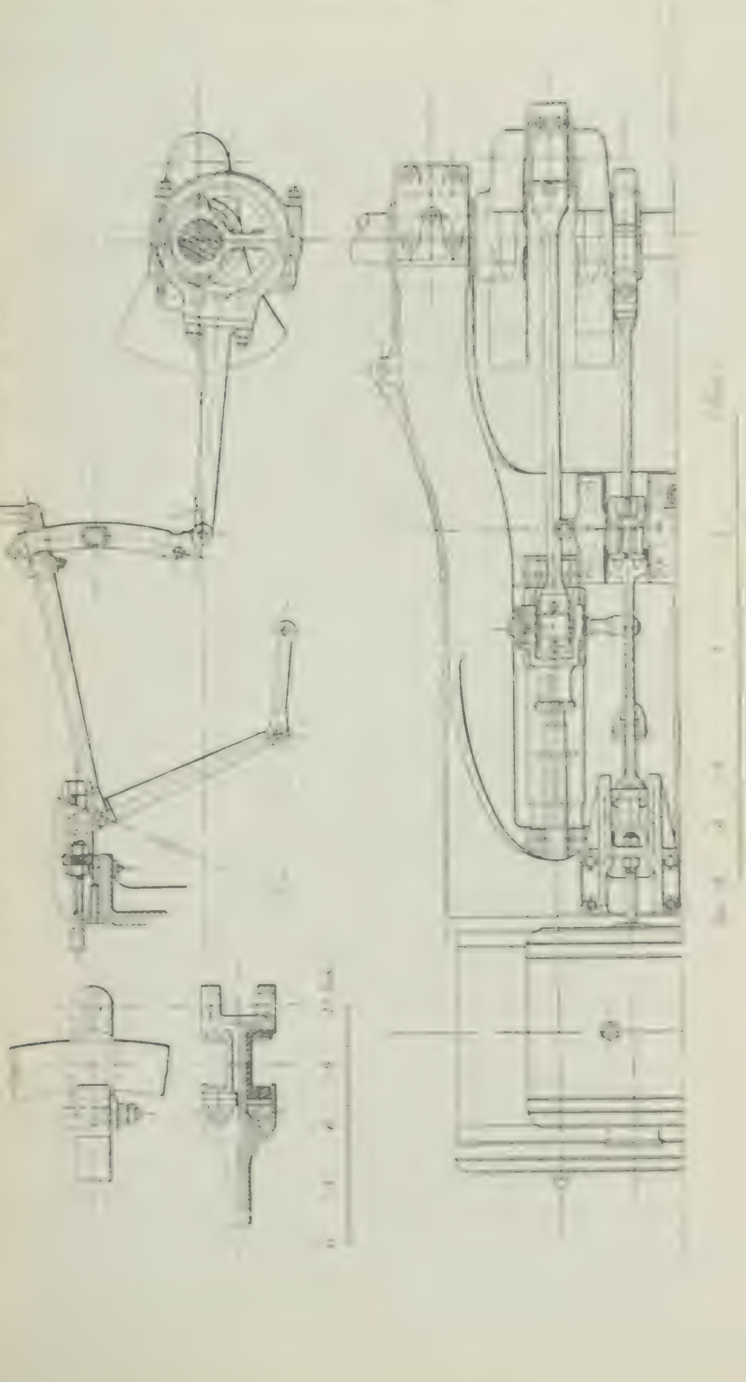


Fig. 60. *Valve Gear for* 13 × 16 *Reversing Engine.*

(Mr. J. D. Twinberrow.)

not wholly avoided by attention to certain details of design and by care in the selection of materials of construction. He had given attention to the problem of replacing the flat stayed surfaces by a water-tube construction, and he believed that in this direction lay the solution of the difficulties arising out of broken stays and cracked fire-box plates.

M. Sauvage, in reply to the written communications, wrote that the remarks quoted by Mr. Marriott (page 463) were taken from a letter of M. Du Bousquet, Locomotive Superintendent of the Northern Railway. The trouble arose from the rapid grooving of the plates. On the Southern Railway the flanged plates were now made of iron. The steel plates used for boilers on the French lines must stand a tensile strength of 35 to 40 kg. per mm.^{2} (22·2 to 25·4 tons per square inch), with an elongation of 30 per cent. for flanged plates, and of 40 to 46 kg. per mm.^{2} (25·4 to 29·2 tons per square inch), with an elongation of 27 per cent. for other plates; the useful length of the test pieces in mm., was calculated by the formula $L = \sqrt{66, 67S}$, S being the transverse section in mm.^{2}. In addition to the tensile test, the plate must be bent cold and entirely doubled up without cracking.

In reply to Mr. Twinberrow's remarks (page 465), flat bar-links had not been used on any of the recent large locomotives of the French Railways.

During the discussion mention was made of the large size of the steam-ports of the Paris-Orléans engines on account of the "squareness" of the diagrams. The following were the exact figures, which showed that the remark was justified:—

Engines Nos. 3001 and 4001, Paris-Orléans Railway.

Cylinder H.P. Diameter = 360 mm. 14·17 inches.
,, L. P. ,, = 600 mm. 23·62 ,,
Port area:
H.P. 126 cm.^{2} (19·53 square inches).
L.P. 220 cm.^{2} (34·10 ,, ,,).
Section of H.P. cylinder = 8·07 port area.
,, ,, L.P. ,, = 12·67 ,, ,,

It was not found possible to increase the size of L.P. cylinder ports, otherwise they would be larger.

As regards the diagrams taken in regular working on locomotive No. 2641 (Nord) (pages 346–347), a question was asked whether the speed was varying when the diagrams were taken. M. Du Bousquet, Locomotive Superintendent of the Nord Railway, states that the speed was uniform when the diagrams were taken, with the exception of the first set on page 346 (starting diagram) and of the second set on page 347 (train No. 112, 23 August 1900). At the time when this last set was taken the acceleration was positive and at a rate of 55 mm. (2·17 inches) per second in a second (variation of speed during a second equal to 55 mm. per second).

THE MEASUREMENT OF DIRECT STRAINS IN TENSILE AND COMPRESSIVE TEST-PIECES.

By Mr JOHN MORROW, M.Sc., M.Eng., of University College, Bristol.

Part I.

1. *Introduction.*—Instruments for the measurement of small strains may be divided into two classes. The first includes all those in which minutely small changes of length are measured directly, with little or no magnification, and which depend on the accuracy of very carefully made micrometer screws or scales. The second consists of those instruments in which the extension or compression of the specimen is greatly magnified by one or more levers or tilting mirrors before the measurement is effected.

The mirror form of extensometer has not been much used in this country owing principally to two causes. These are, first, the instrument is not self-contained, and second, in order to obtain the extension of the centre-line of the specimen two observations have been necessary, one on each side of the specimen.

In an instrument which is not self-contained and which depends upon the reading of the image of a scale in a mirror as seen through a telescope, there may be errors due to,

(*a*) Slight tilting of the specimen and mirror as a whole;
(*b*) Slight alteration of the position of the telescope; and
(*c*) Slight alteration in the position of the scale.

A new form of mirror extensometer, to be of any real value, must, by the elimination of these sources of error, have the advantages of a self-contained instrument, and should give the mean extension of the specimen by means of one scale-reading only.

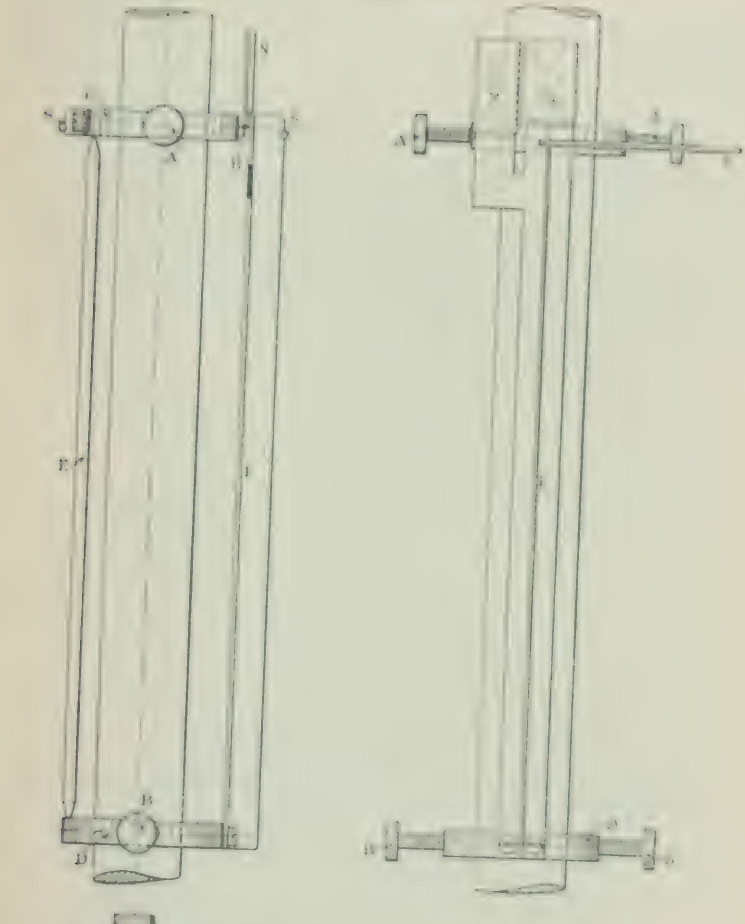
It will be seen that these conditions are realised in the form described in this Part. The special advantages of a mirror extensometer are necessarily retained, namely, the great accuracy of the readings, the provision of any required magnification, and the fact that the instrument, after having been once attached to the specimen, need not again be touched by hand.

2. *The New Form of Instrument.*—The extensometer here described has been used by the author with most satisfactory results. A simple form is shown in Fig. 1 (page 471). It is held in position on the specimen by the four set-screws AA and BB at opposite ends of two parallel diameters. These screws pass through the two horizontal annular pieces C and D, to the latter of which the vertical strip F is rigidly attached. The steel rod E acts as a distance piece between C and D. Its ends merely rest in their respective sockets, and therefore are free to act as ball joints.

When the specimen extends, the face of C, marked G in the plan, will move relatively to F. Between G and the upper end of F a small diamond-shaped piece is inserted as shown at H in each view. This is made of hardened steel, the opposite corners in the horizontal plane being carefully ground to form a pair of knife-edges. It carries a mirror N attached in a vertical position to its upper surface. It will readily be seen that any elongation of the specimen between A A and B B will produce a forward tilting of this mirror.

A second mirror M is attached permanently to F in such a position that the two images of a scale, placed some distance away, may be seen side-by-side in a telescope. The function of the light spring S is two-fold. It maintains a small pressure on the diamond piece between G and F, and at the same time ensures contact between the ends of the rod E and its sockets. For this latter purpose, in some of the earlier forms of the instrument, a special cylindrical spiral spring connecting C and D was used. It was

Fig. 1.—*Mirror Extensometer (New form).*



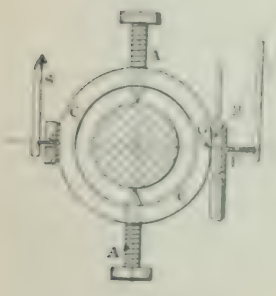
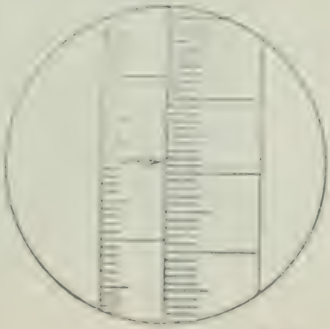


Fig. 2.—Scale.



however found to be unnecessary, and the instrument appears to give rather better results when it is not employed.

In reading the extension of the specimen a convenient mark on one image of the scale is taken as an index, and the reading coinciding with it on the other image is noted each time the load is altered, Fig. 2 (page 471). The index mark is preferably taken on the M image, as it then remains approximately in the centre of the field of view.

In some cases it has been found advantageous to have the mirror M adjustable. It is then fixed on a vertical axis and provided with a slow-motion screw, by means of which it may be rotated about this axis.

3. *Determination of the Magnification.*—The magnification of the instrument can of course be altered at will by placing the scale at a greater or less distance from the mirrors.

If d = normal distance from the scale to the plane of the tilting mirror,
r = distance between knife-edges of mirror base, and
m = magnification due to tilting of upper ring,
then M, the total magnification, is given by

$$M = 2\,d\,\frac{m}{r}$$

This may be called the "ideal magnification."

In the particular instrument described m was found to be 2·220 cm. (0·874 inch) and r = 0·2994 cm. (0·1179 inch), and hence by placing the scale at a normal distance of 202·2 cm. (79·606 inches) a magnification of 3,000 is obtained. The differences of scale-readings divided by this number will be the total extensions of the specimen.

There is in reality a further enlargement due to the magnifying power of the telescope. The scale which has been used is divided to $\frac{1}{40}$ inch. A suitable telescope enables $\frac{1}{10}$th of these to be readily estimated. With the above values the extension of the specimen is then obtained to the nearest $\frac{1}{1,200,000}$ of an inch, or about $\frac{1}{480,000}$ of a centimètre.

As a check upon the magnification, the instrument was attached to the screw of a reading microscope, and simultaneous readings of the extensometer and micrometer scales were taken for a very large number of small displacements. The readings obtained were consistent and within the limits of accuracy of the experiment.

4. *Extension of a Steel Bar.*—In order to test the instrument a specially selected bar of mild steel, 2·54 cm. (1·0 inch) in diameter, was used. The readings were more even when the specimen had been subjected to a considerable load for some time before the experiments were made. A load of 4 or 5 tons was therefore occasionally allowed to remain on the bar for a number of hours.

A large number of observations were made, the load sometimes being applied by one ton intervals and at others by half-a-ton at a time. The variations of the differences of the scale readings per ton or half-ton of load were generally within one and a half per cent. Probably the best test of the instrument was one in which the load was increased by $\frac{1}{2}$ ton intervals from 1 to $3\frac{1}{2}$ tons. Table 1 (page 175) contains the scale readings and their differences for two consecutive series of ascending and descending loads, and it will be seen that the total variation of the differences is less than 1 per cent. of a single reading. The readings are in $\frac{1}{40}$ of an inch, and the length under observation was 20·18 cm. (7·945 inches).

The strain per half-ton of load averages $46 \cdot 71 \times 10^{-6}$, and the corresponding stress is 20,280 kg. per cm.^{2} (288,450 lbs. per square inch). The Modulus of Elasticity is therefore $21 \cdot 46 \times 10^{5}$ in kg.-cm. units, or $30 \cdot 53 \times 10^{6}$ in lbs. per square inch.

5. *Kinematical Investigation.*—The extensometer is shown in diagrammatic form in Fig. 3 (page 174) in its normal position, and also in a displaced position. The free joints are marked by black spots.

The latter position is obtained by assuming G F to be displaced, as at G′ F′, and then obtaining the point C′. With C′ and F′ as centres, arcs are drawn with radii C D and F E respectively. D′ and E′ must lie on these arcs, and the position of A′ is then the point

Fig. 3.

Diagrammatic form of Extensometer in normal and displaced positions.

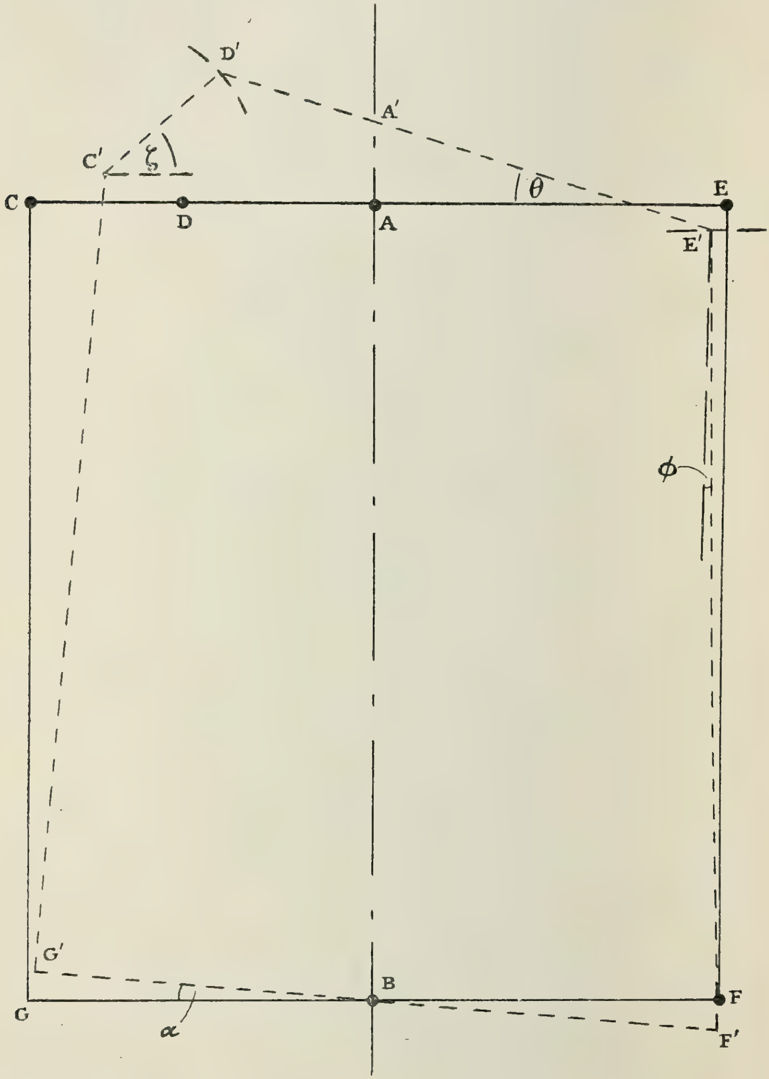


TABLE 1.

Extension of Mild Steel Bar.

Load Tons.	Scale Readings.		Differences.	
	1st Loading.	2nd Loading.	1st Loading.	2nd Loading.
1	−21·1	−21·0	—	—
1½	26·4	26·3	47·5	47·3
2	73·7	73·6	47·3	47·3
2½	120·8	120·7	47·1	47·1
3	168·3	168·2	47·5	47·5
3½	215·7	215·7	47·4	47·5
3	168·5	168·6	47·2	47·1
2½	121·4	121·3	47·1	47·3
2	74·0	74·0	47·4	47·3
1½	26·5	26·5	47·5	47·5
1	−21·0	−20·8	47·5	47·3

where the locus of A intersects the centre line. Of course the displacement shown on the figure is immensely greater than any that would occur in practice.

Let α ζ θ ϕ be respectively the angles turned through by G F, C D, D E, and E F,

l ϵ be the original length and increase of length of the specimen,

s m n the lengths of B F, A D, and C D.

Then we have—

$$m \cos \theta = (m + n) \cos \alpha - l \sin \alpha - n \cos \zeta$$

$$m \sin \theta = (m + n) \sin \alpha + l \cos \alpha + n \sin \zeta - (l + \epsilon)$$

$$s \cos \theta = s \cos \alpha - l \sin \phi$$

$$s \sin \theta = s \sin \alpha - l \cos \phi + (l + \epsilon).$$

To a first order of approximation α and ϕ may be neglected, and we have

$$\zeta = \frac{m+s}{s}\,\frac{\epsilon}{n}$$

The same result is given to a second order in which we retain α, ϕ, θ^2, ζ^2, ϵ^2 since $(\zeta + \alpha)$ is the angle between the fixed and tilting mirrors.

Thirdly, retaining α, ϕ, θ^3, ζ^3, ϵ^3, the result may be expressed—

$$\epsilon = \frac{n\,s}{m+s}\left[(\zeta + \alpha) - \tfrac{1}{6}\,(\zeta + \alpha)^3\right]$$

If R be the scale difference and d its normal distance from the mirror, then—

$$2\,(\zeta + \alpha) = \tan^{-1}\frac{R}{d} = \frac{R}{d} - \frac{1}{3}\,\frac{R^3}{d^3}$$

and therefore—

$$\epsilon = \frac{n\,s}{m+s}\,\frac{R}{2\,d}\left[1 - \frac{3}{8}\,\frac{R^2}{d^2}\right]$$

This investigation shows that to the second order of accuracy the extension of the specimen is given by $\frac{n\,s}{m+s}\,\frac{R}{2\,d}$, and, when working to the third order, the correction to be deducted from the scale reading is $\frac{3}{8}\,\frac{R^3}{d^2}$.

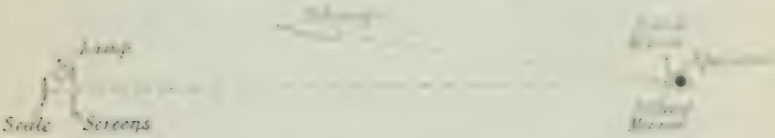
6. *Notes on the General Arrangement and Adjustment of the Apparatus.*—In attaching the extensometer to the specimen it is convenient to make use of a holder. By this means the instrument can be easily and rapidly fixed with the points of the set-screws at the correct distance apart, and arranged at the opposite ends of parallel diameters. The holder also ensures the correct placing of the tilting mirror. A method similar to that employed in the Martens' Mirror Extensometer has, however, been found more convenient for this purpose. In this arrangement a light pointer is attached to the mirror axis, and is adjusted to a cross-mark scribed on the vertical piece F. By this means the mirror axis is always placed in the same position, with its two knife-edges in the same horizontal plane as the points of the upper pair of set-screws.

The cylindrical shape of G, Fig. 1 (page 471), is necessary for two reasons. First, it allows the diamond piece H to have practically line contact with F and point contact with G, thus permitting of slight inaccuracy in the adjustment of the set-screws without endangering the efficiency of the contact; and secondly, it gives a greater degree of freedom to the instrument. Thus there is often a small amount of twist noticeable when stretching a specimen, and the cylindrical shape of G, together with the free ball-joint at the back, allows this twist to take place without disturbing the accuracy of the working of the instrument.

The general arrangement is shown diagrammatically in Fig. 4, the plan of the testing-machine being omitted for the sake of clearness.

After placing the specimen in the machine the holder is removed, and the telescope and scale set up. The scale is illuminated by one or more lamps at one side of, and in front of, the scale, and the light

Fig. 4.—General Arrangement of Apparatus.

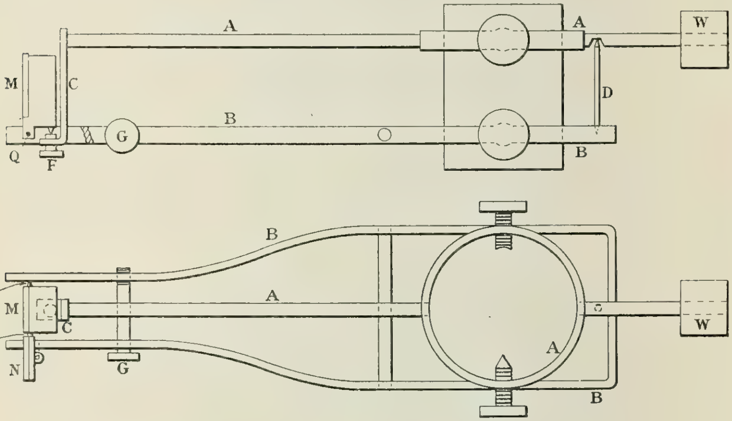


not required is shaded off by two vertical screens. By altering the positions of these screens the two images are easily made to appear side by side, touching but not overlapping, in the field of view of the telescope. The readings can then be taken without difficulty, and in fact, with greater accuracy than when cross-wires obstruct the view.

7. *Adaptation to the Measurement of Compressive Strains.*—For use with short specimens, such as are generally employed for finding Young's Modulus from compression tests, the instrument takes a somewhat different form. In so far as it measures the change of length of the specimen, between two pairs of gauge points, by first converting the displacement into a relative rotation of two mirrors, it is the same in principle.

The particular form shown in Fig. 5 (page 178) is due to Mr. E. L. Watkin, M.A., and the author; its action has been found to be thoroughly reliable. It is made of two frames A and B, the lower of which is attached to the specimen at two points, and the upper at three or four points. In the figure, one of the set-screws in the upper frame is shown with the end formed into a knife-edge from which the central portion has been removed, and this has been found quite sufficient to give the necessary rigidity to the instrument. D is a distance piece with pointed ends, the lower of which acts as a fulcrum about which the lever frame B turns when the specimen is strained. The frame A carries the hanging piece C, through which F is screwed. The flat point of F forms a table on which the pointed steel leg of the tilting mirror M rests. This mirror is also carried by a horizontal axis with fine steel points P Q resting in centres in each arm of B. The screw G is used for ensuring the contact of the extremities of this axis, whilst F enables adjustment of the angular position of the mirror to be effected. The fixed mirror is shown at N, and the balance is preserved by the weight W.

Fig. 5.—*Compression Instrument.*



Many modifications of both these instruments have been tried, but none appear to be more satisfactory than those here described The large amount of experimental work connected with the perfecting of the instruments has been carried out in the Testing Laboratory of University College, Bristol. In most of this work the author has been fortunate in having the assistance of his colleague, Mr. E. L. Watkin, M.A.

Part II.

This Part contains a brief description of the more important instruments hitherto used for measuring tensile or compressive strains in test-pieces within the elastic limit. One of them, namely that made by Messrs. Buckton and Co., of Leeds, has not been previously described.

1. *Magnitude of the Changes and Limits of Measurement.*—The object of such experiments is to find the stress-strain relations for the material, and the deformations are so small that they cannot be determined without the aid of some special apparatus. Thus an iron or steel bar, 10 inches long, is stretched less than $\frac{1}{100}$ inch when the elastic limit is reached. For an accuracy of about 1 per cent. the measurements must therefore be correct at least to the nearest $\frac{1}{10000}$ inch. To obtain the same accuracy with a compression piece 2 inches long, the delicacy of reading would have to be increased five times. These may be looked upon as the lowest limits of accuracy permissible in any form of extensometer.

Now the limit of resolving power of the human eye is given as $\frac{1}{250}$ inch. With the aid of a microscope this can be reduced to $\frac{1}{100000}$ inch. A carefully graduated vernier attached to a micrometer screw may read to $\frac{1}{[illegible]}$ inch, whilst measurements depending on the principle of the interference of light may conveniently reach $\frac{1}{10,000,000}$ of an inch.

2. *Errors in producing the Required Strains.*—With such delicacy of reading, considerable care is required to ensure that the changes of length observed are those due only to the elasticity of the

specimen. For this, it is necessary that the temperature should be constant. If an instrument has a magnification of 1,000, it is possible that a change of even $\frac{1}{20}$° C. may begin to affect the readings. Therefore, after attaching an instrument to a specimen, a short pause should be allowed before the experiment is commenced, so that the thermal conditions may become normal. Other sources of error are due to the method of attaching the extensometer. The measurements must be made directly on the test-piece and should be on two opposite filaments of it. This is necessary in order to counteract the effects of slight bending of the specimen due to oblique gripping or non-homogeneity of the material, and to avoid or determine errors due to slight tilting of the specimen as a whole.

The points between which the changes of length are measured should be sufficiently remote from those at which the load is applied, otherwise local strains, caused by the necessarily imperfect method of application of the load, will be included. When this is done by means of a collar on the specimen, and its distance from the gauge points is one-half the greatest breadth of the specimen, this error has been calculated to be about 10 per cent. of the strain at the point, whilst at $1\frac{1}{2}$ times the breadth it is only 0·3 per cent. For accurate work therefore the distance should be at least 1 to $1\frac{1}{2}$ times the greatest cross dimension. Even when these precautions are taken, the deformations are only those of the outer surface of the test-piece and do not necessarily give a true account of what takes place in the interior. It must further be noticed that the sensitiveness and the calibration of the testing machine used are important factors in determining the limit of accuracy obtainable.

3. *Conditions affecting the Accuracy of the Instruments.*—In this section the author proposes to enumerate some general principles, the fulfilment of which appears to be advisable, and in fact almost essential, in the design of efficient strain-measuring appliances. A careful consideration of these conditions should enable an idea of the practical value of any instrument to be estimated. They will not be repeated when describing the various forms in use.

(1) The measurements should be taken on two opposite sides of the specimen. This condition has already been referred to.

(2) There should be the greatest possible freedom from constraint. The change of length of the specimen is required, and, consistently with its accurate determination, the different parts of the instrument should have the greatest freedom both as regards relative translation and rotation. Neglect of this generally prevents the instrument from returning exactly to its initial position when the strain is removed.

(3) The size and mass of the principal moving parts should be as small as possible. This is advisable, not only that they may respond readily to the displacements communicated to them, but that they should not be affected by disturbing influences such as air-currents, vibrations, &c. If the moving parts are supported by friction only, as is generally the case, the small unavoidable vibrations vary the amount of the supporting force, and if the parts are heavy accidental displacements may result. The construction of more than one instrument has been discontinued, owing, in part at any rate, to this cause.*

(4) The relative displacements of the parts of the instrument should be kinematically determinate. Under this heading it is intended to include the avoidance of errors due to faulty transmission or conversion of motion. In mirror apparatus, for example, the plane of the reflecting surface should pass through the axis of rotation; the error due to reading off a flat instead of a curved scale should be determined; the mirrors should be optically plane, and some method of correcting or allowing for errors due to small displacements of the specimen, telescope, or scale should be provided.

Again, if rollers are used, as in the Bauschinger instruments for converting linear to rotary motion, they should be accurately circular. Stromeyer has successfully employed wires for this purpose. In some cases, however, the wire was only one millimetre in diameter, and it is doubtful whether such a small roller could be trusted to be circular in section. In micrometer apparatus, errors such as those due to the imperfections of screws are included.

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* For example, the Buzby Extensometer, and another described in Martens' "Handbook of Testing Materials," Part I, pages [illegible] 6

(5) It should not be necessary to touch the instrument by hand during an experiment. Apart from other reasons, it is sufficiently obvious that handling an instrument is liable to alter slightly its adjustment.

(6) Any measurements, which have to be independently made, should be such as are easily capable of sufficiently accurate determination. The independent measurements include that of the gauge length of the specimen and, in mirror apparatus, the normal distance of the scale from the reflecting surface. Thus, if an accuracy of say 0·1 per cent. is desired, the distance between the gauge points of a 10-inch specimen must be obtained at least to the nearest $\frac{1}{100}$ inch.

(7) The instrument should be supported at the gauge points only, and no part of it should be in contact with any portion of the testing machine. In Professor Kennedy's mirror apparatus of 1879,* the mirror spindle was connected to the frame of the machine. This was one of the reasons which led him to cease using it in favour of the mechanical apparatus described later.

(8) The instrument itself should be free from strains, especially those which are liable to vary with the load on the specimen.

The above eight conditions may be taken as indicating what should be expected in an ideal instrument, and it should be stated here that some reliable extensometers are now in use in which one or other of these conditions is not fulfilled.

An idea of the uniformity of measurements obtained by different instruments can be obtained from the reports of the "Calibration of Instruments" Committee of the British Association.†

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* Described and illustrated in "Engineering," 1879, vol. xxviii, pages 245 and 248.

† Report of British Association 1896, page 538, and 1897, page 424.

Extensometers.

FIG. 6.—*Kennedy*

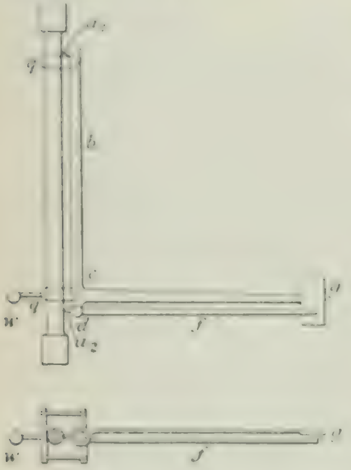


FIG. 7.—*Ashcroft.*

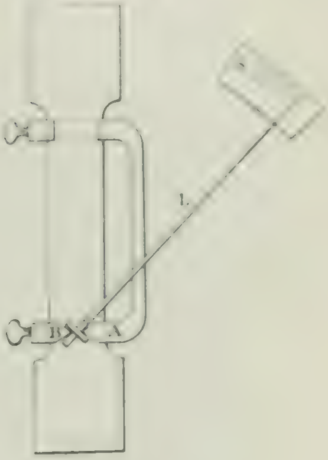


FIG. 8.—*Martens.*

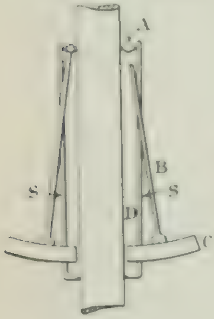


FIG. 9.—*Stromeyer.*

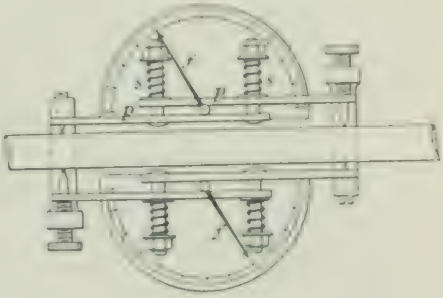
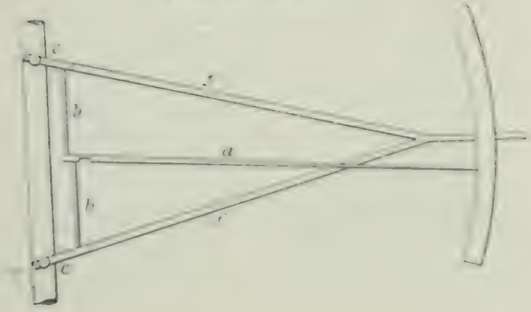


FIG. 10.—*Goodman.*



INSTRUMENTS IN WHICH THE DISPLACEMENT IS CONSIDERABLY MAGNIFIED BEFORE THE MEASUREMENT IS EFFECTED.

4. *Mechanical Magnification.—Kennedy's Extensometer.**—This is shown in Fig. 6 (page 483). It consists of a framework *b c* carrying the lever *f*, pivoted at *d*. It is kept in position by elastic bands or springs *q q*, a weight *w* helping to preserve the balance. When the specimen extends the gauge points a_1 a_2 move apart, and the other end of the lever *f* moves over the plane *g* which is covered with section paper. The readings can be taken to the nearest $\frac{1}{10,000}$ or $\frac{1}{20,000}$ inch.

Martens' Lever Extensometer.†—*See* Fig. 8 (page 483). This is similar in principle to Kennedy's. The lever is, however, formed by a diamond-shaped piece A, to which the arm B is connected, and the scale consists of a curved bar C attached to the frame D.

The illustration shows the instrument arranged for taking simultaneous readings on two opposite sides of the specimen. S is a spring pressing the two frames inwards, and so enabling them to be held on the specimen. When the magnification is 50, readings can be conveniently taken to $\frac{1}{500}$ mm.

Stromeyer's Extensometer.‡—Fig. 9 (page 483) is of the roller type. The rollers are made of wire of small diameter. They carry index fingers *f f*, and are held in position between flat plates *p p* by the pressure of the springs *s s*. Results have been obtained in which each scale division represents $\frac{1}{10,000}$ inch, and a further estimation could be made.

Goodman's Extensometer.§—From Fig. 10 (page 483) it will be seen that this consists of a 100 to 1 lever *a*, moving over a graduated scale. The pillars *b b* transmit the motion of the clips *c c* to this lever. The scale is carried by a very light frame *f*, and it is evident that an extension of the specimen produces a bending strain in this frame. Nevertheless, when the instrument is calibrated on an independent measuring machine it can be used for reading to $\frac{1}{10000}$ inch.

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* Proceedings Institution of Civil Engineers, vol. lxxxviii, page 24.

† Martens' "Handbook of Testing Materials," vol. I, page 546.

‡ "A Strain Indicator for Use at Sea," Transactions, Institution of Naval Architects, 1886, page 33.

§ "Engineering," 11 Sept. 1896.

Messrs. Joshua Buckton and Co. supply the instrument shown in Figs. 11 and 12 (page 486). No account of it has been previously published, and the author is indebted to Mr. J. Hartley Wicksteed, President, for a description of its action, and for the drawing from which Fig. 11 was produced. It is particularly interesting as an example of an extensometer which, although partly supported by the framework of the machine, preserves the accuracy of its readings when the specimen moves bodily. It is designed for a specimen that lies horizontally. In Fig. 11 (page 486) A and B are the gauge points at which the test-piece T is gripped by two pairs of set-screws. C and D are levers, the former being continued in the form of a light aluminium quill to carry the index vernier at V. The scale S is attached to the bar E which is pivoted to C at F, and carries the set-screws A A. The points H K and P Q are kept at a fixed distance apart by their respective cross-bars, and the lengths of these can be varied for specimens of different gauge length. At H and K also the instrument is supported by points on small sliding blocks carried on stationary brackets. The principle of its action can be understood if we imagine the points A H and K to remain fixed whilst the specimen extends by a displacement of B. The points Q and P will then move through a greater distance than B in the ratio $\frac{Q\ K}{B\ K}$. Since the point F must remain in position, the index V will move through a distance which is further magnified in the ratio $\frac{V\ F}{F\ P}$, and its displacement can be read on scale and vernier.

Again, suppose the points H and K remain fixed and that the specimen suffers a bodily displacement in the direction of its axis, the points Q P and F will then move by amounts proportional to their distances from H K, and the reading of the vernier will not be

Extensometer.

FIG. 11.—*Buckton.*

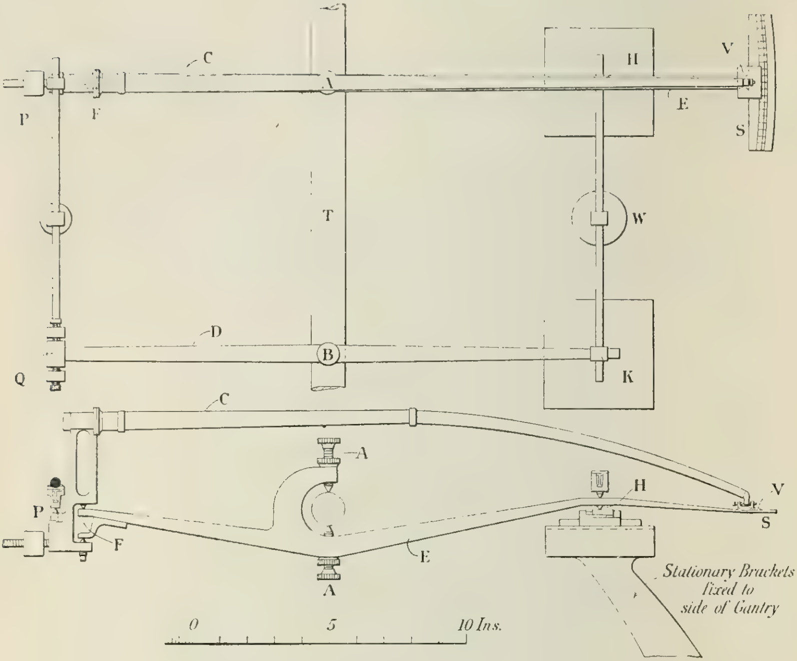
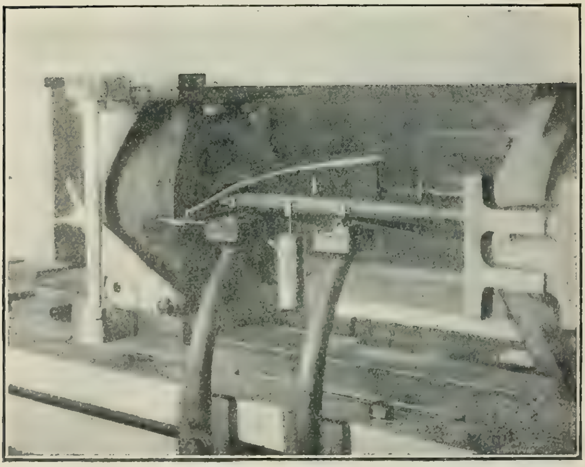


FIG. 12.—*General view of the above Extensometer.*



affected. Mr. Wicksteed states that the instrument is accurate in working and returns exactly to zero on relieving the tension. The shortest distance between the centres is one inch, and there is no lost motion. The total magnification is 50, and the elongations are read on the vernier to $\frac{1}{10000}$ inch.

Ashcroft has described a single lever extensometer* shown diagrammatically in Fig. 7 (page 483). The knife edge A is rigidly fixed to the upper end of the gauge length, whilst that at B is attached to the lower end. The small arm of the multiplying lever L is between these knife edges, whilst the extremity of the larger arm indicates the extension on the scale S. With a lever 21 inches long a magnification of 200 is obtained.

Other instruments which may be mentioned belonging to this class are those of Colonel Paine,† Bach, and Neel and Claremont.‡ The last of these is arranged to automatically record the elastic strains. Bach's is described later.

5. *Optical Magnification.*—The introduction of mirror apparatus for the measurement of strains is principally due to Bauschinger. In the following instruments the change of length of the specimen is converted into rotary motion of the mirror, and is read by means of a telescope and scale.

Bauschinger's Instrument § is shown in Fig. 13 (page 488). Two clips *a a* and *b b* are pressed against the specimen; *c c* are light springs which press outwards against rollers *d d*. These rollers, which are of caoutchouc, are carried by the clip *b b*, and themselves carry the mirrors *g g*. As the specimen extends the rollers rotate, and these rotations are measured by means of the telescopes *e e* and scales *f f*.

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* Proceedings, Institution of Civil Engineers, vol. clv. page 266.

† Martens' "Handbook of Testing Materials," page 545; Unwin's "Testing of Materials of Construction," page 215; and Abbot's "Testing Machines," page 86.

‡ "Stahl und Eisen," 1895, pages 575 and 673; also "Martens' Handbook of Testing Materials," page 549.

§ *See* Bauschinger's "Maschine z. prüfen Festigkeit, etc.," München, 1882; also "Mittheil. Mech. Tech. Lab. München," H. 1 u. 3.

The results are recorded to $\frac{1}{10,000}$ mm. To Bauschinger belongs the credit of first systematically taking double measurements on opposite sides of a test-bar.

Fig. 13.—*Bauschinger.*

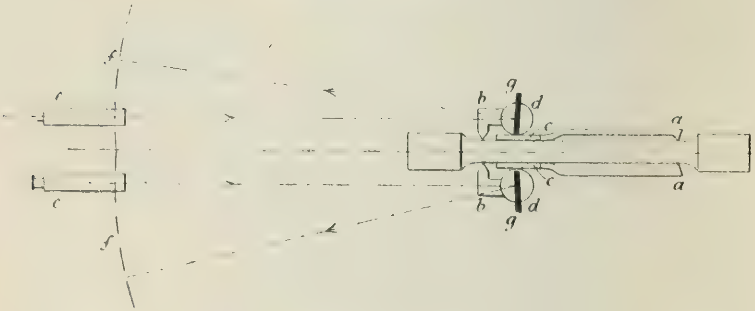
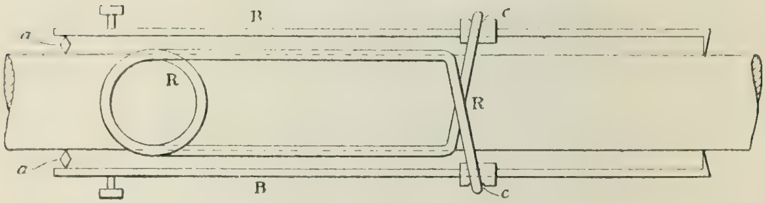


Fig. 14.—*Martens.*



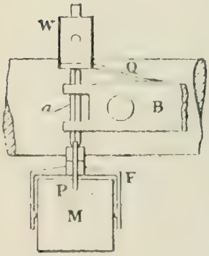


Fig. 15.
Front Elevation.

*Martens' Mirror Extensometer.**—This is an improvement on Bauschinger's, as it has a mirror on each side of the specimen; but, as is shown in Figs. 14 and 15, the rollers are replaced by pieces of steel *a a* of rhombic section, the inner edges of which bear against the test-piece. It will be noticed that the axles are done away with, *a a* being supported by friction only. In Fig. 14 the mirrors and mirror-frames are not shown. Fig. 15 is a front elevation of the mirror attachment on one side of the specimen. M = the mirror carried in the frame F by means of pivots centred in small holes drilled in the glass. An adjusting screw is on the reverse side of the mirror, by means of which it may be rotated about its axis, and this screw is opposed by the spring P. The weight of these parts, being borne on the rhombic piece *a*, is balanced by a weight W. Q is a pointer attached to *a*, arranged so that, when its end is adjusted to one edge of the strip B, the mirror is in its correct initial position. These instruments bear against a round specimen at four points, and it is clearly necessary to provide an additional constraint preventing rotation about the axis of the specimen. This is effected by allowing the spring R to rest in grooves at *c c*. With a flat specimen contact is made on each side by two points at one extremity of the gauge length, thus ensuring absolute rigidity. Two telescopes are required for reading; more recently one has been tried, but not with complete success. Measurements may be obtained to the nearest $\frac{1}{250,000}$ inch.

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* See Martens' "Handbook of Testing Materials."

*Kirsch's Extensometer** differs from Martens' by using one telescope only, and by having contact with flat as with round specimens, by two points instead of a knife-edge at one extremity of the gauge length.

Henning's Mirror Extensometer.† —This differs in two important respects from the Martens' instrument. The mirror spindle passes through a frame, in which there is a small screw for adjusting the initial position of the spindle. The instrument is transformed into a single unit by connecting the two sides together at the end away from the mirrors. This connection is of rectangular shape, having

* "Wochenschrift des Oesterreichischen Ingenieur und Architekten-Vereins," 1891, page 139.

† Transactions, American Society of Mechanical Engineers, May 189[illegible], page 849.

two set-screws for attachment to the specimen, and is divided into two halves joined by a hinge. It can therefore be opened and attached to the test-piece without the necessity of marking off the gauge-length. The readings are taken to $\frac{1}{500,000}$ inch.

6. *Single Mirror Apparatus.—Unwin's Single Mirror Apparatus.**—This is an attempt to obviate the necessity of taking double readings, by attaching the instrument by four set-screws *a b* and so obtaining motion of the mirror due to the mean extension of the test-bar. In Fig. 16, C is a distance-piece fitted in punch marks between E and F, and supporting the weight of the former; the screw S is for adjusting and holding F normally to the axis of the test-piece. The spring P presses against a roller carrying a mirror M, and causes it to rotate when the length *a b* suffers any alteration.

Hartig's Apparatus † is rather complicated. It is shown diagrammatically in Fig. 17. A and B are two frames, each clamped to the specimen at three points. T T are thin steel tapes fastened to the frame B and passing over pulleys P P, which are carried by the other frame. The pulleys transmit the motion to the compensating beam C, and this gives the mean motion by another tape to the mirror axis Q.

Martens has also constructed a single mirror apparatus ‡ on the principle indicated in Fig. 18. The frames A and B are attached to the test-bar by four set-screws S S. The upper frame is steadied in position without constraint by a spring C attached to A, but free to slide on the neck of the set-screw in B. Two rods D D stand on the points of screws in the lower frame, and on their upper ends carry the bridge E. This bridge is supported freely between the ends of D D, and points F F on A; it carries the mirror axis and mirror as at M in the plan. The short arm of the mirror is thus

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* Proceedings, Physical Society, vol. viii, page 178.

† "Civilingenieure," 1893, part 6.

‡ *See* Martens' "Handbook of Testing Materials," Part I, page 590.

Fig. 16.—*Unwin.*

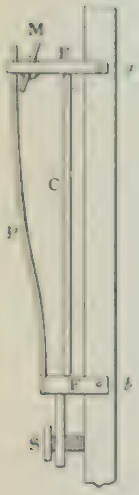


Fig. 17.—*Hartig.*

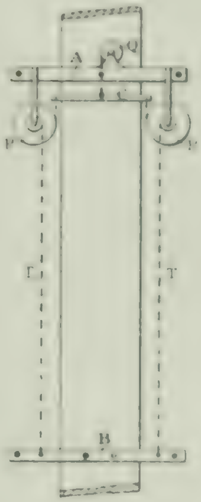
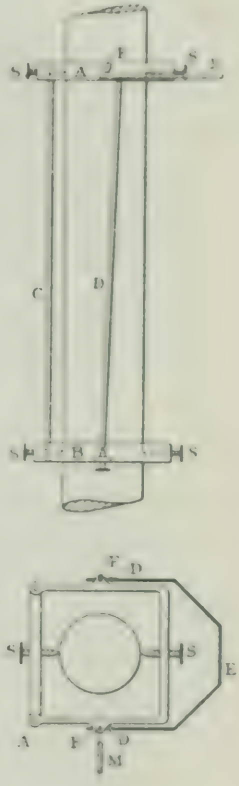


Fig. 18.—*Martens.*



the distance F D on the plan: there is therefore some difficulty in determining it with sufficient accuracy.

INSTRUMENTS IN WHICH THE DEFORMATION IS MEASURED WITH LITTLE OR NO MAGNIFICATION.

7. *Extensometers with Micrometer Screws.*—All these instruments have to be touched by hand many times during an experiment. One of the earliest was designed by Professor R. H. Thurston in 1875, this being the first in which two micrometer screws were placed symmetrically on each side of the test-piece, and in which electric contact was employed.

Riehlé Bros. of Philadelphia construct the instrument shown in Fig. 19 (page 493). It consists of two rings A B secured to the specimen by four set-screws S S. They are prevented from rotating by the springs P P in contact with the specimen, and the distance between them is measured during the experiment by a micrometer end gauge M. Readings may be estimated to $\frac{1}{10,000}$ inch.

*Henning's Micrometer.**—In Fig. 20 (page 493) *m m* are the micrometer screws carried by the lower frame B. Each frame A and B grips the specimen between two steel points *h h* and two knife-edges *c c*. When the specimen extends, the ends of the screws *f f* are brought into contact with the plugs *g g*, and this is indicated by the ringing of an electric bell, the circuit of which passes through *f g*. The extension is read on the vertical scales *e e* and on the micrometer heads *m m*. The bars *d* are used in fixing the clips the correct distance apart. They are moved away when the instrument is in use. The frames A and B can be opened for attaching to the specimen.

Marshall's Extensometer differs from Henning's in having open frames which can be merely placed about the test-piece. The micrometer screws and contacts are placed nearer the lower frame. The adjusting bars *d* are omitted, and the knife edges *c c* are replaced by spring rollers.

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* Transactions, American Society of Mechanical Engineers, 1885, page 479.

Extensometers with Micrometer Screws.

Fig. 19.—*Riehlé.*

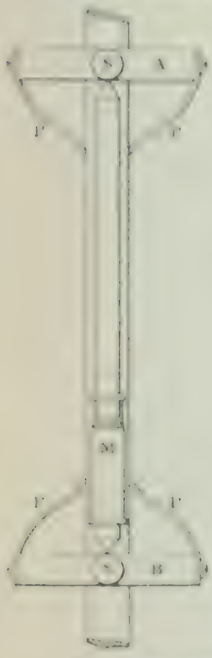


Fig. 20.—*Henning.*

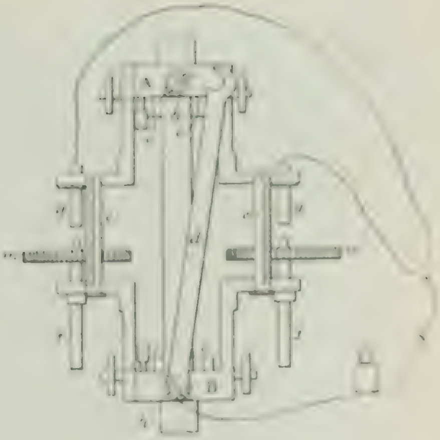


Fig. 21.—*Unwin.*

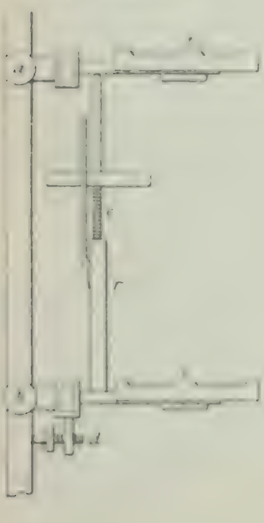
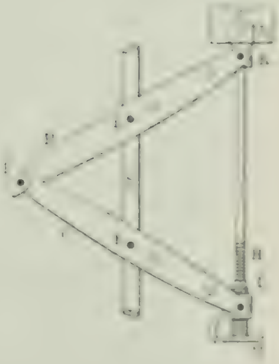


Fig. 22.—*Garrett.*



The Yale Extensometer is very similar to Marshall's, except that there is a vertical rectangular bar to maintain the frames in parallelism and adjust the instrument to gauge-length, the spring rollers being omitted.

Unwin's Screw Extensometer.[*]—In this instrument many of the kinematical errors of the three preceding are entirely avoided. It is shown in Fig. 21 (page 493); *a a* and *b b* are the four set-screws passing through the two clamps or stirrups. The lower one carries the micrometer screw *e*, on the top of which the upper one rests. The lower clip is set level by adjusting the screw *d* and spirit level *c*, and the upper one by the micrometer screw *e* and level *f*. The bar *r* is of adjustable length to suit different test pieces. The instrument described reads to $\frac{1}{10,000}$ inch.

Garratt's Extensometer[†] is shown in Fig. 22 (page 493). Two pairs of parallel steel plates B and C are pivoted together at F, and attached to the specimen by screws E E at the gauge-points. A micrometer screw M is pivoted to the lower pair of plates. It has twenty-five threads to the inch and two hundred divisions on the disc. There is a mechanical multiplication of two. The length of the instrument can be adjusted by the check-nut L. The spindle H passes through the guide K, and carries a pointed pin on its upper extremity. This pin is part of the mechanism of an aneroid barometer, and, when the specimen extends, its motion produces a displacement of the aneroid needle. The measurement is effected by turning the micrometer screw M until the needle is brought back to its original position, the delicacy of the aneroid being greater than that of the screw.

8. *Microscope Reading.—Cathetometers.* The use of cathetometers for measuring strains has been abandoned because of their

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[*] Proceedings, Physical Society, vol. viii, page 178; *see* also Unwin's "Testing Materials of Construction."

[†] Proceedings, Institution of Civil Engineers, vol. cxxviii, page 321.

inconvenience and limited efficiency for such purposes. Instruments are however constructed on the principle of the reading microscope or comparator. Some of these are described in this section, and others will be found amongst the instruments used in compression tests.

Jenny's Apparatus[*] (devised by Mr. G. Starke) consists of two micrometric microscopes adjustable both along and across the test-piece. It reads to about $\frac{1}{\text{[illegible]}}$ inch.

Ewing's Extensometer[†] is the instrument which has been used for the most accurate work in this country. It is shown in its latest form in Fig. 23 (page 496). The two clips B and C are attached to the specimen, each by two set-screws. The former carries the rod B′ ending in a round point P which engages with a conical hole in C. B B′ are jointed together so that the specimen may twist a little without affecting the bearing at P. When the specimen extends, P serves as a fulcrum for C, and hence the point Q is displaced twice the distance. This displacement is measured by the microscope M, carried on B, the motion of Q being brought into the field by the hanging rod R which carries a mark on which the microscope is sighted. The readings are taken on a micrometer scale in the eye-piece of M, and are effected without touching the specimen. The screw L is to bring the mark initially to a convenient part of the scale. The readings may be estimated to $\frac{1}{\text{[illegible]}}$ inch. A clamping bar is provided for attaching the instrument correctly and to the required gauge length.

9. Extensometers for Use on Actual Structures.

Many of the foregoing instruments, such as those of Stromeyer and Colonel Paine, could be used to ascertain the alterations of

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[*] Jenny's "Festigkeits Versuche," Vienna, 1878.

[†] Proceedings Royal Society, vol. lviii; see also Ewing's "Strength of Materials."

Extensometers.

Fig. 23.—*Ewing.*

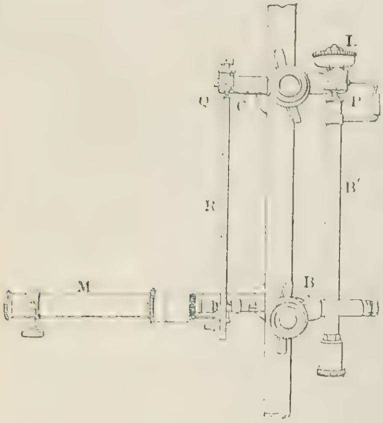


Fig. 24.
Henning.

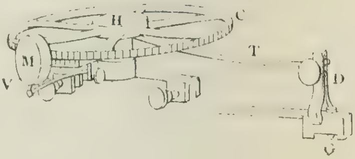


Fig. 25.
Manet, Rabut, and Deistler.

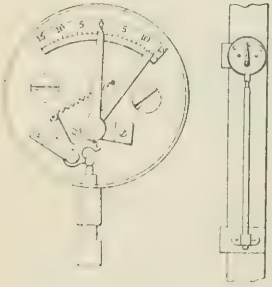
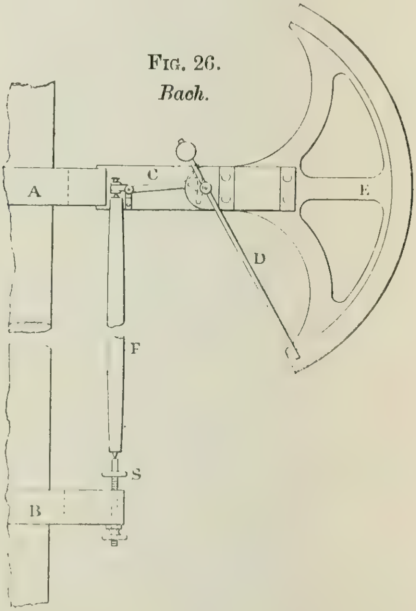


Fig. 26.
Bach.



length of different members of structures. Some instruments, however, have been specially constructed for this purpose.

*Cowper's Extensometer.**—This was used on long bars for the Kieff Bridge in 1850. It consisted of a light tube about 4 feet long, with a fork at each end which fitted against pins attached to the test-bar. One of the forks was free to slide, and carried a vernier on which the extensions were observed.

Dupuy's Extensometer† consists of a 20 to 1 lever with its fulcrum on the bar to be tested. The lever terminates in a pointer moving over a graduated arc carried by the fulcrum piece. The short end of the lever is attached to a bar one mètre long, and the other end of this is fastened to the test-piece. Each millimetre movement of the pointer represents a stress of 1 kg. per mm^2. (i.e. 0·635 ton per square inch).

Henning's Extensometer‡ with wrapping connector, is shown in Fig. 24 (page 496). It is carried on a telescopic rod (not shown), one end of which is clamped to the test-bar at one gauge mark, and the other end is free to slide in the post D. D is attached to the bar at the other gauge mark by the point G and a clamp. A thin steel tape T, fastened to D, passes round H. Elongation of the test bar therefore causes the large divided circle C to rotate, and the extension is read to $\frac{1}{10,000}$ inch by the vernier V and the magnifying glass M.

Le Chatelier§ describes an apparatus consisting of a thin diaphragm of large area acting on a vessel full of water, with which is connected a glass tube of small diameter open to the air. Alteration of length of the specimen slightly alters the diaphragm, and so causes the water to rise or fall in the tube. With a magnification thus produced of 1,000, and a gauge length of 36 inches, the extension-reading of a wrought-iron bar is about 3 inches for a stress of one ton per square inch. The instrument requires constant calibration.

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* Proceedings, Institution of Mechanical Engineers, 1878, page [illegible].

† Annales des Ponts et Chaussées, 5th series, vol. xiv, page [illegible].

‡ Transactions, American Society of Mechanical Engineers, [illegible], page [illegible].

§ Annales des Ponts et Chaussées, June 1890.

*The Instruments of Manet, Rabut,** *and Deistler* † consist of a rod, one end of which is fixed to the specimen, while the other is in contact with a toothed arc gearing into a pinion moving a light pointer over a graduated dial, the pivot of the arc being fixed to the specimen at the other extremity of the gauge length. The principle is shown in Fig. 25 (page 496).

10. INSTRUMENTS FOR USE IN COMPRESSION TESTS.

Many of the following instruments could also be used in tensile experiments. Those mentioned below are, however, more generally used in compression tests, and are usually described in that connection. Similarly, those already considered can be employed for compression experiments, provided the test-column is sufficiently long to admit of their use. Instruments in which the measurements are taken between portions of the testing machine are not described.

Bach's Extensometer. ‡—Fig. 26 (page 496) shows the apparatus used by Bach for crushing tests of concrete blocks. The instruments are placed on opposite sides of the specimen and secured by four set-screws in each frame A and B. A supports the double levers C and D, and the graduated arc E. B carries the adjusting screw S which supports the distance piece F. F can be adjusted to suit different lengths of specimens. The segmental end of C is connected to the roller of D by a thin steel tape. The magnification is 300, and the readings can be taken to about $\frac{1}{75,000}$ inch.

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* Annales des Ponts et Chaussées, Nov. 1895.

† Technische Blätter. Vierteljahrschrift Polytechnischen Vereines, Böhmen, 1889, page 17.

‡ Bach's "Elasticität und Festigkeit" (Berlin), page 105.

The Instrument of Durand Claye[*] is very similar to Bach's; but the thin steel tape is not used, the segmental arm gearing by means of small teeth with a pinion on D.

Martens' Mirror Apparatus for Crushing Tests.[†]—For cubes of stone or concrete, Martens has used the instrument shown diagrammatically in Fig. 27 (page 500). The rod R touches the specimen S by two forked knife-edges A formed at its lower end. At the upper end is the mirror fulcrum M, pressed against the saddle C by the rubber band or spring E. This saddle rests by two forked knife-edges at B and the tail-piece at D. At A and B are shown small quantities of wax or resin-putty which may be used to ensure the permanency of the position of the knife-edges.

Martens' Apparatus for Short Blocks[‡] is constructed on the lines of Fig. 28 (page 500). It consists of two pieces C D, each provided with a gapped fulcrum A B bearing on the specimen, thus providing four points of contact. R is a roller and M the mirror fulcrum. There is of course a similar apparatus on the other side of the specimen, and the two are braced together by a cylindrical spiral spring on opposite sides of the specimen. The apparatus is used for gauge distances of 1 cm. (0·4 inch) when the readings are estimated to about $\frac{1}{500,000}$ inch.

Unwin's Instrument for Short Blocks.[§]—Fig. 29 (page 500). This combines a lever l_1 having a mechanical magnification of $2\frac{1}{2}$, with a micrometer microscope M. The rectangular frame c_2 is clamped to the specimen by four set-screws; it carries the pillar p, on which rests the knife-edge of the upper frame c_1. The upper frame is attached to the block by two set-screws. The ends of l_1 and l_2 carry silvered plates with a fine scratch on each. The compressions are

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[*] Annales des Ponts et Chaussées, 1888 XV. Text XVI, s. 193.

[†] Martens' "Handbook of Testing Materials," pages 581-2.

[‡] *Ibid.* pages 581-2.

[§] Unwin's "Testing Materials of Construction," page 225.

Extensometers.

Fig. 27.—*Martens.*

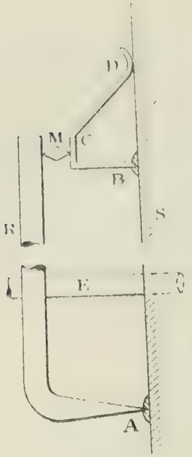


Fig. 28.—*Martens.*

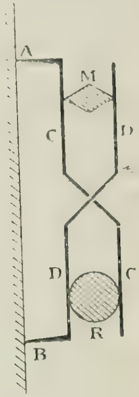


Fig. 29.—*Unwin.*

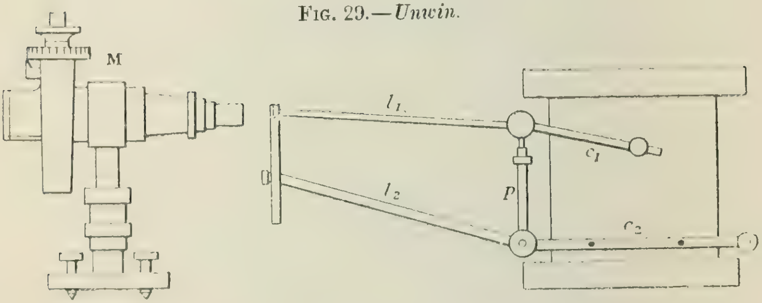
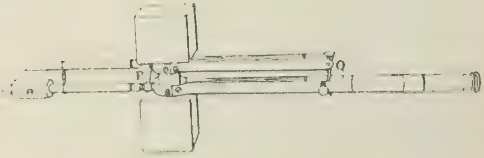


Fig. 30.—*Ewing.*



measured by observing the distance between these scratches during the test, and this can be determined to [illegible] inch. The instrument gives by a single reading the mean compression of the two sides of the block.

*Ewing's Extensometer for Short Blocks.** From Fig. 50 (page 500) it will be seen that this is substantially the same as the corresponding instrument used for tensile experiments. The mechanical multiplication is however increased to ten times, the distance of Q from the axis being nine times that of P. The motion of Q is transferred to the field of the microscope by a vertical piece at Q jointed to the lever P Q. The microscope is sighted on a small piece of glass, on which are two fine horizontal lines at a distance apart of $\frac{1}{40}$ inch. The microscope is adjusted to make these lines include 500 units of the eye-piece scale. Each unit then corresponds to an extension of $\frac{1}{200,000}$ inch.

Conclusion.—It is scarcely necessary to state that, in the compilation of the second part of this Paper, the author has drawn largely from such standard works as Professor Martens' "Handbook of Testing Materials" (translated by G. C. Henning), and Professor Unwin's "The Testing of Materials of Construction," and also from the various technical and scientific publications to which references are made. Whilst the descriptions given are not exhaustive, it is hoped that all the more important instruments have been mentioned. It is possible however that some may have been overlooked, and the author has, in fact, heard of a few extensometers of which he is unable to find any published account.

The Paper is illustrated by 50 Figs. in the letterpress.

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* Proceedings Royal Society, vol. lviii.

MEMOIRS.

Walter Seckford Brewster was born on 10th May 1846. At the age of eighteen he was apprenticed to Messrs. Laird Brothers, Birkenhead, and, on the expiration of his time in 1868, he entered the locomotive works of Messrs. Beyer, Peacock, and Co., Gorton. After working for a few years in the fitting and erecting shops, he was employed by the firm in delivering locomotives to various railways in Europe, South America, and other countries, and subsequently in Australia, where he finally settled. He acted as their representative from 1878 to 1894; and in the latter year he commenced business on his own account in Sydney. His death took place at his residence in Carlton, Sydney, New South Wales, on 12th February 1904, in his fifty-eighth year. He became a Member of this Institution in 1890.

Field Marshal H.R.H. **The Duke of Cambridge**, K.G., was born on 26th March 1819, being the son of Adolphus Frederick, the first Duke of Cambridge. His Royal Highness was therefore grandson of George III., and first cousin of Queen Victoria, and consequently first cousin once removed of His Majesty the King. Prince George of Cambridge, as he was called in his early days, began his military career at the age of nine years, when he received from George IV., as King of Hanover, the patent of colonel in the Hanoverian Army. Notwithstanding the high military rank thus given, he subsequently did duty as a private soldier in the regiment. In 1837 he entered the British Army as a colonel by brevet, and in the two succeeding years was attached to the staff at Gibraltar. He next was attached to the 12th Lancers, and did duty in Ireland for the following two years. Then he was transferred to the 17th Light Dragoons, taking full command, and in this capacity he had to take an active part in 1842 in suppressing the riots in the manufacturing districts. From 1843 to 1845 he served as Colonel on the Staff in the Ionian Islands, and in the latter year was promoted to the rank of Major-General. He was next appointed to the command of the Dublin District, which he retained until 1852. During this period he succeeded—in 1850—to the Dukedom of Cambridge. From 1852 to 1854 he was Inspector-General of Cavalry, and shortly after was appointed Major-General in the Crimean Force, and on 19th June in the same year was promoted to the rank of Lieutenant-General, his command being the Guards and Highland Brigades, which formed the first division of the expeditionary force. At Alma and Inkerman the first division were in the thick of the battles. The Duke's health shortly after gave way, and he was invalided home. In July 1856 Lord Hardinge resigned the command of the British Army, and on the 15th of the month His Royal Highness succeeded to that office. At the early age of thirty-seven he assumed the command which he held continuously for thirty-nine years. He was promoted to the rank of Field Marshal in 1862, and became Commander-in-Chief in 1887. In October 1895 the late Duke laid down the reins of office, and with the official recognition of his past services by the Sovereign in the appointment to the Honorary Colonelcy in Chief to the Forces, His Royal Highness's career of fifty-eight years as an active soldier came to an end.

Apart altogether from the Army, the Duke of Cambridge was indefatigable in public work, and gave his name and time to many national institutions. He was President of the London Hospital, a Governor of King's College, and from 1854 had been President of Christ's Hospital. He was Ranger of St. James's Park, the Green Park, Hyde Park, and Richmond Park. The Duke of Cambridge also held the titles of Earl of Tipperary and Baron Culloden; he was a Knight of the Garter, a Privy Councillor, Knight of the Order of the Thistle, and held the rank of Knight Grand Cross in the leading Orders. He was also D.C.L. of Oxford, and LL.D. of Cambridge. He honoured this Institution by accepting in 1892 Honorary Life Membership, to which the Council had elected him, and on two occasions—1892 and 1897—had attended the Anniversary Dinner, replying to the toast of "The Queen's Land and Sea

Forces." Latterly his health had been failing, and his death took place at his residence, Gloucester House, Park Lane, London, on 17th March 1904, within a few days of his eighty-fifth birthday.

CHARLES COOK was born at Ballater, Aberdeenshire, on 22nd July 1863. He received his education at Ballater School, and Chanonry School, Aberdeen. In 1878 he commenced an apprenticeship in the iron foundry and engineering works of Messrs. Hall, Russell and Co., of Aberdeen. On the completion of his time in 1883, he went to sea as marine engineer, subsequently receiving a first-class engineer's certificate from the Board of Trade. In 1885 he became chief engineer, and in that capacity sailed for the next five years to foreign parts, the last three years being spent wholly on the Chinese coast. In 1890 he became a partner and director in the firm of Messrs. Barry, Henry and Co., Aberdeen Iron Foundry, Aberdeen, and in 1893 proceeded to London to take charge of that agency. His death took place suddenly at his residence at Crouch End, London, on 14th June 1903, in his fortieth year. He became a Member of this Institution in 1896.

WILLIAM COOPER was born at Easington, Durham, on 31st December 1843. In 1860 he commenced an apprenticeship of two years with the West Hartlepool Steam Navigation Co., and served a further two years with Messrs. Pile, Spence and Co., of West Hartlepool, on the termination of which he continued with the latter firm for over two years as foreman and draughtsman. In 1866 he went as engineer and draughtsman to the Iron, Coal, and Harbour Works at Tondu and Porthcawl for Messrs. John Brogden and Sons, with whom he remained until 1872; he was then engaged by Messrs. Edward Shotton and Co., as superintendent of various ship and machinery work. With this firm he stayed until 1883, and then started on his own account in North Shields as consulting engineer and marine surveyor, and acted for several firms on the Tyne and in Leith, to which latter place in 1890 he transferred his business. He invented an improved slide-valve indicator. His death took place at Leith on 8th May 1904, at the age of sixty. He became a Member of this Institution in 1899.

EDWARD COWARD was born at Stand, Lancashire, on 23rd April 1831. After being educated privately and at Owens College, he entered the works of Messrs. Melland and Coward, at Heaton Mersey and Manchester, spinners, weavers, dyers, bleachers, and finishers. On the death of his father, he succeeded him in the partnership with Mr. Melland. In local affairs he was the only chairman of the Heaton Norris Local Board, resigning his position on the conversion of the Local Board into a District Council. For some years he was chairman of the Lancashire Insurance Co., until its absorption in the Royal Insurance Co., and was also chairman of the Ebbw Vale Steel, Iron, and Coal Co. He was a director of the Great Northern Railway Co., and had charge of erecting the Manchester Goods Yard in Deansgate. This building has accommodation for over 400 wagons, and there is stabling for 130 horses. His death took place at Eastbourne on 10th April 1904, in his seventy-third year. He became a Member of this Institution in 1875; and was also a Member of the Institution of Civil Engineers.

CHARLES MERSON DAVIES was born at Newton Longville, Buckinghamshire, on 9th November 1849, being the second son of Mr. Charles Davies, who was for seventeen years an engineer on the Great Indian Peninsula Railway. He was educated principally at Dollar Academy, Clackmannanshire, from 1860 to 1867, and in the latter year commenced an apprenticeship with Messrs. Dübs and Co., of Glasgow. Having passed through the various shops and the drawing office, he went in 1871 as an improver in the running shed of the Caledonian Railway at Motherwell. In September 1873 he went to India as mechanical engineer to Messrs. T. C. Glover and Co., contractors for the construction of the Rajputana State Railway from Agra to Nusserabad, and was engaged in the erection of the principal iron bridges on that railway until 1875, when he was appointed assistant locomotive superintendent of the same railway. In 1877 he was in charge of the pilot engine which ran in advance of H.R.H. the Prince of Wales' train from Agra to Jeypore. He next became locomotive, carriage, and wagon superintendent of the Holkar and Scindia-Neemuch State Railway in

1878, and officiated in the same capacity for six months in 1882 on the Rajputana State Railway. He then transferred his services to the Nagpur and Chhattisgarh State Railway, which was afterwards designated the Bengal-Nagpur Railway. In 1889 he visited Australia and Tasmania, and resigned his appointment in India in 1891, when he took up the post of chief engineer to Messrs. Dubs and Co., with whom he remained till his death. Among his various inventions may be named an appliance for cooling railway carriages, which obtained a bronze medal at the Calcutta Exhibition in 1883; also a portable drilling machine for locomotive boilers, and a plural drilling machine for the same purpose, which was fully described in the Proceedings 1894, page 521, by Mr. J. W. Hulse during the discussion on Mr. Samuel Dixon's Paper on "Drilling Machines for Cylindrical Boiler Shells." In 1893 he brought out a quadruple tapping machine for locomotive fire-boxes, which, together with the drills before mentioned, is in daily use at Messrs. Dubs' Works. Whilst in India he devoted much of his leisure to the designing and building of small sailing boats for use on the various lakes near which he was stationed; and since settling in Scotland his chief recreation was turning in ivory and African black wood, in which he had executed some elaborate and delicate designs. In the autumn of 1903 he was taken ill, and after great suffering and undergoing an operation, he gradually sank, his death taking place at his residence in Pollokshields, Glasgow, on 19th June 1904, in his fifty-fifth year. He became a Member of this Institution in 1880; and he was also a Member of the Institution of Engineers and Shipbuilders in Scotland.

Edward John Mines Davies was born at Swansea on 12th February 1861, and was the grandson and son of the late David Davies and Son, proprietors of the Cwmfelin Tin Plate Works, near Swansea. He received his theoretical training at the University College, Bristol, and Owens College, Manchester, and obtained a Whitworth Scholarship in 1881. He also received a Miller prize from the Institution of Civil Engineers, and was Honours Medallist of the Science and Art Department and City and

Guilds of London Institution. From 1875 to 1880 he served his apprenticeship at the Avonside Engine Works, Bristol, and had since been with many leading engineers both at home and abroad, among which may be mentioned Messrs. Goodfellow, of Hyde, near Manchester, Messrs. R. Hornsby and Sons, of Grantham, Messrs. Sulzer Brothers, of Winterthur, Switzerland, The Great Eastern Railway Company, Mr. William Shelford, of Great George Street, London, and was at the time of his death engaged by the Underground Electric Railways Co., of London. He was also for some years lecturer of Mathematics and Engineering at the Gravesend Technical School, Wandsworth Technical Institute, and the South Tottenham Polytechnic. His death took place in London from enteric typhoid fever, on 18th June 1904, at the age of forty-three. He became a Member of this Institution in 1885.

Frank Douglas was born in Hackney, London, on 5th March 1867. He was educated at Croydon High School and at the College de Marine, Dieppe, and received his technical education, in conjunction with his apprenticeship, at the College of Science and Art, Glasgow. In 1884 he was apprenticed for five years to Messrs. Robert Napier and Sons, of Glasgow, and on its termination was employed by Mr. I. A. Timmis, of Westminster, on the installation of electric lighting and electric brakes on the railways in Russia. In 1891 he went to sea as a marine engineer in the employ of Messrs. Lamport and Holt and the Eastern Telegraph Co. until 1897, when he obtained the chief engineer's certificate of the Board of Trade. In 1898 he was appointed resident engineer to the East Anglian Ice Co., at Lowestoft, superintending the erection of the whole of the plant and buildings; and then became consulting engineer to the Ramsgate Pure Ice Co., and refrigerating engineer to Messrs. R. A. Lister and Co., and also managing engineer to the London and Provincial Ice Co. In 1903 he was offered the position of engineer and general manager in Africa of the North American and African Cold Storage Co., and proceeded to Delagoa Bay to erect the first store in that country. His death took place from an aneurism, while on the voyage home from South Africa, on

18th April 1904, at the age of thirty-seven. He became an Associate Member of this Institution in 1903.

CHARLES JOHN GALLOWAY was born in Manchester on 25th April 1833. He served his apprenticeship from 1846 to 1851 with his father and uncle, Messrs. W. and J. Galloway, of Knott Mill Iron Works, Manchester; and became a partner in the firm in 1856. On its conversion into a company in 1889 he was elected chairman, a position which he occupied up to the time of his death. During his career he superintended the erection of the Furness Railway Viaduct over the Ulverston Sands, also the erection of Southport Pier, and devoted much time and attention to the development and improvement of the Galloway boiler. He took great interest in the International Exhibition of Paris in 1878, and for his services in connection therewith he was made a Chevalier of the Legion of Honour; and on the occasion of the Exhibition in 1889 he was promoted to the rank of Officer of the same Order. He was also vice-chairman of the Manchester Jubilee Exhibition of 1887. He held numerous directorships in various industrial companies, including that of the Manchester Ship Canal, and he was chairman of the Vulcan Insurance Co. He was a Justice of the Peace for the City of Manchester, and for the County of Cheshire. His death took place suddenly at his residence in Knutsford, on 13th March 1904, in his seventy-first year. He became a Member of this Institution in 1866.

WILLIAM AUGUSTUS GORMAN was born at Limerick on 6th October 1835, being a son of the late Captain Gorman, of Limerick. He received his engineering training in the works of his uncle, Mr. Siebe, at Westminster Bridge Road, London, and also in Mr. Scott Russell's Works at Millwall. His career has been identified with that of the well-known firm of Messrs. Siebe, Gorman and Co.—established by the late Mr. Augustus Siebe in 1820—in which he became a partner in 1870. In addition to the diving and submarine engineering work, his firm started in 1855 the construction of ice-making and refrigerating machinery, which was then considered a great novelty, and fitted up the steamers "Fifeshire," "Morayshire," and "Nairnshire," for the New Zealand meat trade. This particular branch of the business was however given up some years ago. He devised many improvements in diving apparatus as well as in ice-making machinery, and his firm have been awarded numerous medals, including a gold medal at the International Fisheries Exhibition in 1883, and two gold medals at the International Health Exhibition in 1884. In addition to the invention of a diver's speaking apparatus, Mr. Gorman successfully introduced the telephone attached to the diver's helmet, the conducting wire being inlaid in the signal line. Besides submarine electric lamps, rock-boring apparatus, etc., his firm also construct air-locks for cylinder sinking, and air-lock bells for use in making and levelling foundations and for the removal of rock. In 1882 he read a Paper before this Institution on "Improved Appliances for Working under Water or in Irrespirable Gases" (Proceedings, page 179); and took part in discussions both on that subject and on "Refrigerating Machinery." His death took place at his residence in South Kensington, London, on 4th February 1904, at the age of sixty-eight. He became a Member of this Institution in 1879.

Joseph Bennett Howell was born in Swansea on 19th February 1818. When a young man he went to Sheffield, and was in the employ of more than one firm now extinct. Subsequently he became associated with Messrs. Naylor, Vickers and Co. (now Messrs. Vickers Sons and Maxim), whom he represented with much success for a number of years. Relinquishing that position, he commenced business on his own account, as steel and file manufacturer. By his inventive genius and special knowledge of steel making, he speedily gained a wide reputation for improvements in the manufacture of steel, and attained a prominent position in the steel trade. At the Exhibition of 1862 he received the only medal awarded for excellent quality of cast steel, and for rolls made of cast steel. Before the days of the Bessemer and the Siemens - Martin processes, he manufactured crucible mild cast-steel, and was the first to make steel ingots of heavy weights. He originated the application of such steel for constructive purposes. This new steel was called "Homogeneous Metal," and the first boiler made of steel, and the first steel boat made, were constructed of this metal. This boat, the "Ma Robert," was built by Messrs. Lairds, of Birkenhead, for the use of Dr. Livingstone on the Zambesi River, Central Africa. He constructed and erected in 1867 the steel chains of the Suspension Bridge over the Moldau at Prague, these being the first steel chains used for a bridge of this kind. His inventions were both numerous and varied, and he was the first to apply mild steel to the manufacture of locomotive boiler tubes. In 1868 he founded the Brook Steel and File Works, Sheffield. The success attendant upon the invention of mild steel for boiler tubes ultimately led to the establishment of a separate department for the manufacture of steel tubes, and in conjunction with his son Mr. S. Earnshaw Howell (also a Member of the Institution), he established the Sheffield Tube Works at Wincobank, near Sheffield. They were subsequently amalgamated with the Brook Steel and File Works, and formed into a private company, of which he was the chairman until his death, which took place at his residence in Leamington on 4th June 1904, at the age of eighty-six. He became a Member of this Institution in 1861; and was also a Member of the Society of Arts, and of the Institution of Naval Architects.

Henry Arthur Livock was born on 27th March 1862. After being educated at a private school in Liverpool, he was apprenticed in 1878 to Messrs. Higginbottom and Stuart, engineers, of Liverpool, passing through the various shops and drawing office. In 1884 he became a draughtsman in the locomotive department of the Lancashire and Yorkshire Railway, and in 1886 was appointed locomotive superintendent of the Buenos Aires and Great Southern Railway, which position he held until 1890. From that year until 1900 he was partner in the firm of Evans, Livock and Co., of Buenos Aires and London, representatives in South America for Messrs. Kitson and Co., the Monkbridge Iron and Steel Co., the Vacuum Brake Co., etc. Subsequently he was in business as an engineer in London, as managing director of the London Engineering Co., and Monarch Door Controller Co. When on business in the Argentine Republic, in the course of his travels up the rivers he caught typhoid fever, which developed itself on the passage home. By the time the steamer reached Southampton his condition was regarded as very serious and he was moved to the isolation hospital, where his death took place on the following day, 9th February 1904, in his forty-second year. He became a Member of this Institution in 1903.

Cornelius McLeod Percy was born at Newmains, Lanarkshire, on 30th July 1846. At the age of seven he went with his parents to settle in England, and received his education at the public schools in connection with the works of Earl Granville at Cobridge, North Staffordshire, and of the New British Iron Co., at Congreaves, in South Staffordshire. In 1860 he was apprenticed with the latter company, and his apprenticeship was continued and completed with the Wigan Coal and Iron Co. Subsequently he held various and important positions in the engineering department of this company, remaining with them until 1882, when he commenced practice in Wigan as a consulting engineer. He was connected during the greater part of his life with the Mining and Technical School, which he entered as a student in 1862. On the death of the master, he was appointed at the age of twenty-one as joint lecturer with the late Mr. Ralph Betley. When the Wigan Mining School Committee, the County Borough Council, and the Lancashire County Council agreed to maintain and manage the school, he was appointed principal, and occupied that position until his death. A strong advocate of the cause of technical education, he delivered valuable lectures in different parts of the country, and these led to the establishment of technical classes in those places. He displayed great activity in connection with the erection of a new college in commemoration of the Diamond Jubilee, and his illustrated lectures there attracted large numbers of students. He wrote extensively for various mining journals both at home and abroad, and was for some years editor of "The Science and Art of Mining." During that period he prepared a number of small books for the use of mining students, and was engaged on re-writing "The Mechanical Engineering of Collieries" at the time that his health broke down. He was a member of the

Wigan Town Council for several years, and had been a candidate for Parliament on two occasions. His health for some time had been in a very unsatisfactory state, when he was advised to take a voyage to Australia and New Zealand. He returned home however without having derived any benefit from the change, and his death ensued on 19th June 1903, in his fifty-seventh year. He became a Member of this Institution in 1874; and was also a Member of the Institution of Mining Engineers.

ROBERT CORNELIUS QUIN was born in London on 4th February 1865, and was educated at a public elementary school. From 1882 to 1889 he was a pupil of, and afterwards general assistant to, Mr. J. N. Schoolbred, and during this time he was connected with the electric lighting of the construction works of the Forth Bridge, the Calne Village water supply, the Warkworth Harbour Works, &c. In 1886 he secured his first appointment in the Electricity Department of the Bradford Corporation, and in 1891 was appointed chief assistant of the Brighton Corporation Electricity Works, carrying out extensive alterations and additions. In 1896 he became electrical and tramway engineer of Blackpool, during which time he was responsible for the conversion of the old conduit line—the first of its kind in the country—to the overhead trolley system. He was also consulting electrical and tramway engineer to the West Bromwich Town Council. In January 1904 he was at Tamney, Co. Donegal, with several engineering friends, engaged in surveying a quarry, and while standing on the pier a tidal wave swept in and washed him into the sea. An attempt to rescue him was unsuccessful, but his body was subsequently recovered and brought back to London. His death took place on 11th January 1904, in his thirty-ninth year. He became a Member of this Institution in 1899.

BRIDGMAN RUSSELL was born in London on 18th February 18[illegible], and was educated at Vale College, Ramsgate, from 1871 to 1877. In the latter year he was articled to Messrs. Rosser and Russell, heating and ventilating engineers, of Charing Cross and Hammersmith, and passed through the shops and drawing-office. On the termination of his apprenticeship in 1881, he continued with the same firm as draughtsman, and had charge of various works until 1885. He was then appointed manager of the engineering department of Messrs. Comyn Ching and Co., of London, with whom he remained until 1889, when he started business on his own account as Messrs. Russell and Co., Berwick Street, London. Since that time he has carried out throughout the country various works of water supplies, heating, ventilation, and sanitation arrangements, and designed and manufactured a small lift and force pump. His death took place at Boscombe on 20th January 1904, in his forty-first year. He was elected an Associate Member of this Institution in 1898, and was transferred to full Membership in 1900.

WALTER HENRY WILSON, until 1902 one of the principals of Messrs. Harland and Wolff, Belfast, was born in Belfast on 4th November 1839. After finishing his education at Chester College, he adopted naval architecture and engineering as his profession, and entered the works of Messrs. Hickson and Co., iron shipbuilders, Belfast, as an apprentice in 1857. Messrs. Hickson's yard was the forerunner of the present world-famed Queen's Island establishment of Messrs. Harland and Wolff, with which Mr. Wilson was connected during his professional career, and of which he became a partner in 1874. He showed great industry and remarkable talents as an apprentice and subsequently an official, and later still, a principal in the firm, and became one of the most capable exponents in the art of shipbuilding and engineering. As a draughtsman and designer he had few equals, and nearly every department of the works, as well as the vessels constructed by the firm, bore evidence of his mechanical genius. He was possessed of great inventive capacity, and many of the appliances brought out by him have been eminently successful. The following are some of the principal mechanical improvements and developments he was responsible for:—Improvements in cabins by which staterooms were rendered more comfortable by an ingenious arrangement of the berths; invention of a steering gear in which springs were applied to the arms, spokes, or other parts of the tiller, yoke, or quadrant, thus creating an elastic medium between the rudder head and the steering chains, and permitting the chains to be always kept equally tight, while allowing the rudder to yield to severe shocks or strains. A second patent of his, taken out in 1890, for improvements in the structure and arrangement of steam steering-gear developed and perfected this principle for minimising by means of steel springs the effect of the shocks and strains to which the rudder of a ship is subjected. A notable feature in the later gear was the placing of the engine immediately beside the tiller with a worm on crank-shaft driving a wheel on a vertical intermediate shaft, the shaft carrying a spur pinion driving a spur wheel tiller secured to the rudder head through an elastic medium consisting of flat or spiral steel springs. In this gear one of the great advantages is the dispensing with the chains formerly required, and the engine can be drawn completely out of gear with the tiller or quadrant when it is required to steer the ship by hand steering. This improved steering-gear, as invented and worked out by him in 1890, is generally considered to-day to be one of the best, safest, and most reliable available, and has not only been fitted in all vessels of Messrs. Harland and Wolff's build since that date, but has been adopted in many others by owners and builders both British and foreign.

Many other inventions, also, were the creation of his brain and unremitting energy, including a combined square deck-house sidelight and ventilator; boat disengaging gear; improvements in ships' watertight doors; and improvements in ships and other structures of metal plates riveted together—an improved form of connection for the transverse joints of shell and other plated structures, commonly known as "Harland and Wolff's scarphed or lapped butts." Amongst other improvements introduced by Mr. Wilson, or for which he was chiefly responsible, is the structural arrangement of the stern of vessels for carrying the shaft within the hull instead of the old-fashioned brackets outside, and he also conceived the idea of the single-plate rudder now almost universally adopted in large steamers, instead of the old arrangement which gave so much trouble. He avoided publicity in every way, but was persuaded at the beginning of 1904 to become President of the Belfast Chamber of Commerce, a position he held at the time of his death. He was also a member of the Northern Counties Committee of the Midland Railway. On the occasion of the Summer Meeting of this Institution in Belfast in 1896 he was chairman of the Reception Committee, and rendered great service in connection with the various arrangements for the visit. His death took place suddenly in the train between Kilrea and Portrush on 14th May 1904, in his sixty-fifth year. He became a Member of this Institution in 1888; and was also a Member of the Institution of Civil Engineers, and of the Institution of Naval Architects.

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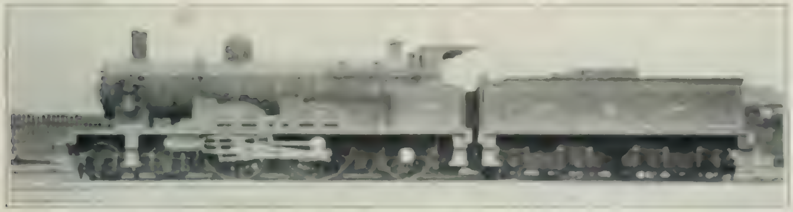
Fig. 1. No. [illegible] Nord [illegible]



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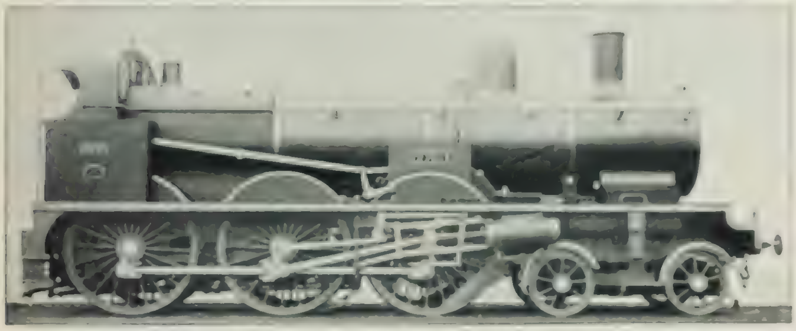

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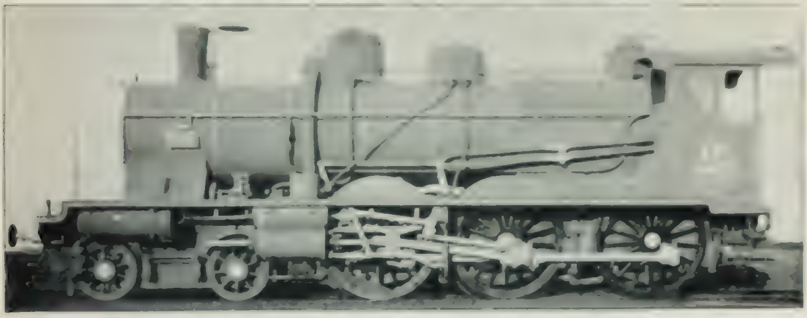
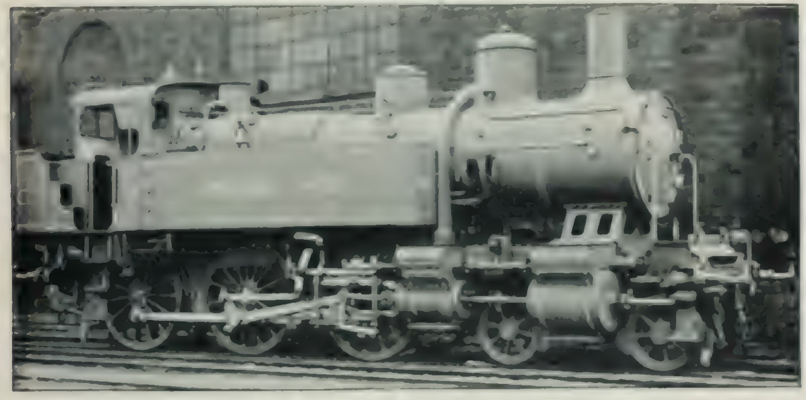


Fig. 4. No. 42. Tender Compound [illegible]



Mechanical Engineer [illegible]

COMPOUND LOCOMOTIVES IN FRANCE.

Fig. 5. No. [illegible] Paris-Orléans [illegible] type.
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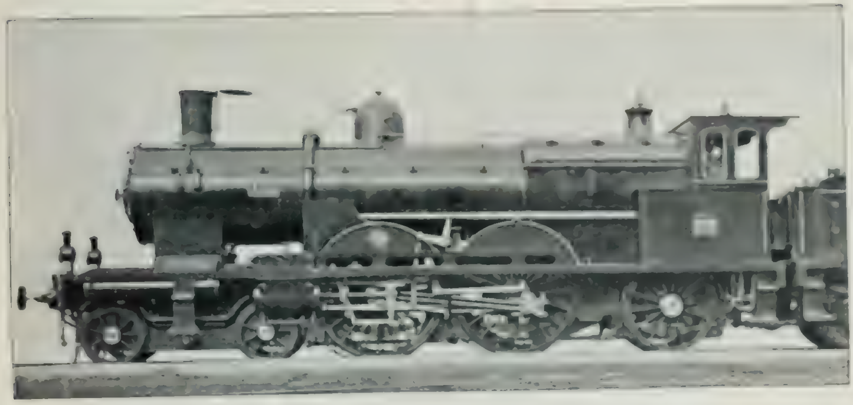
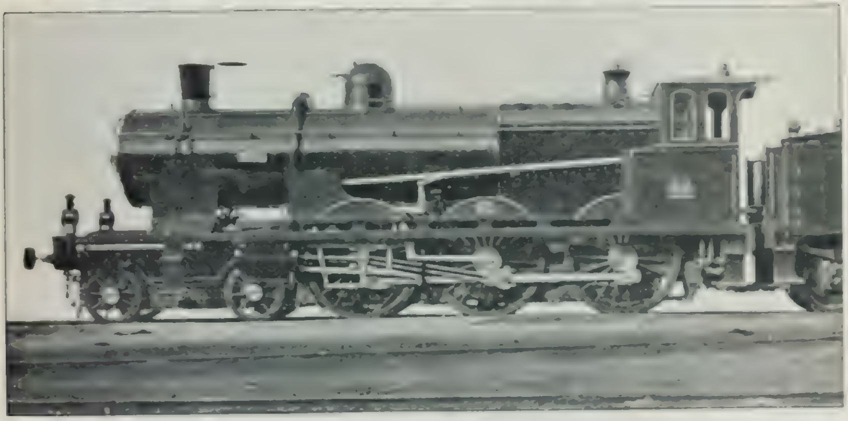


Fig. 6. No. [illegible] Paris-Orléans [illegible]



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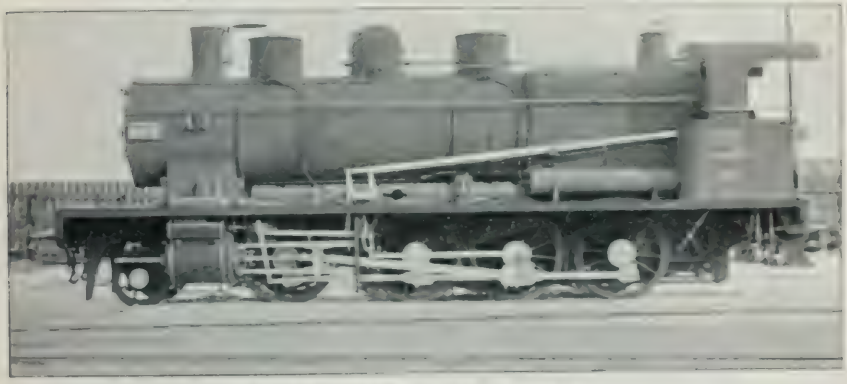


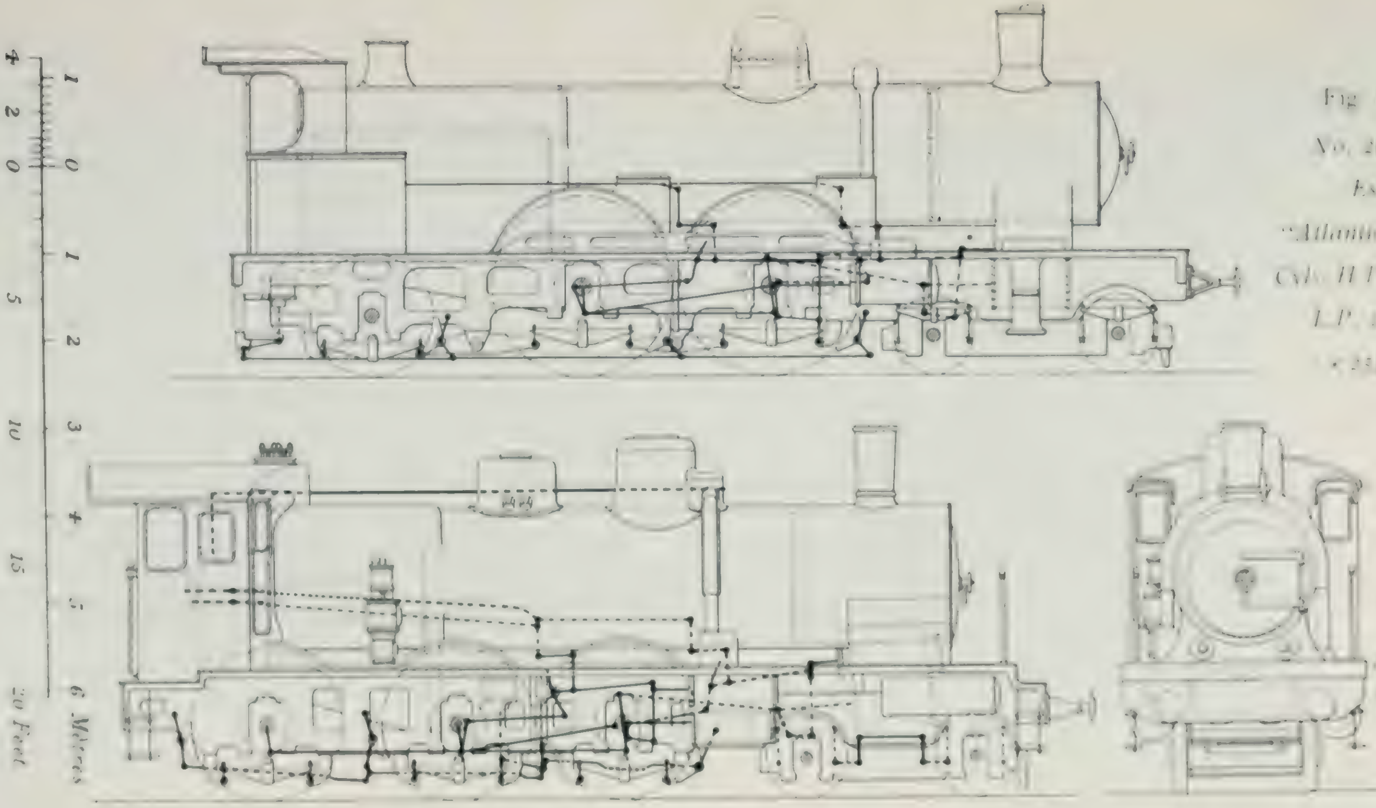


Fig. 8.
No. 2601.
Est.
"Atlantic" type.
Cyls. H.P. 13⅜in.
L.P. 22in.
× 25¼in.

[illegible]

Mechanical Engineers 1904.

COMPOUND LOCOMOTIVES IN FRANCE

Fig. 10.
Nos. 3101—3102.
Est.
Cyls. H.P. 13¾in.
L.P. 22in.
× 26in.

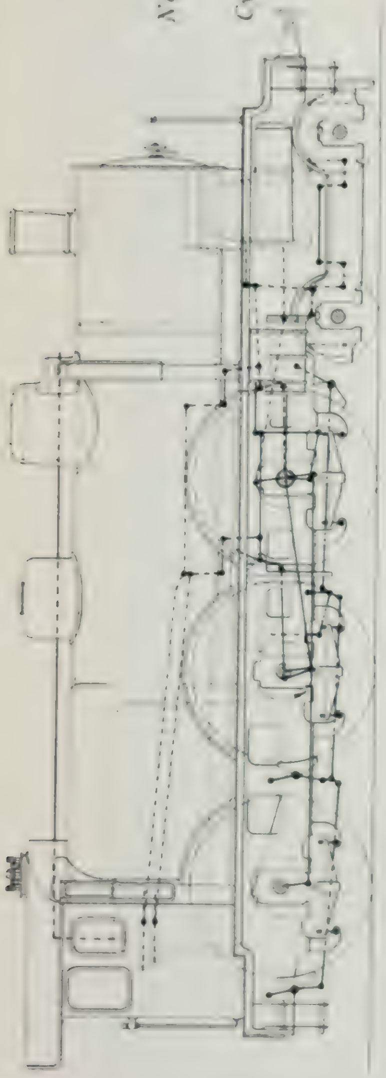
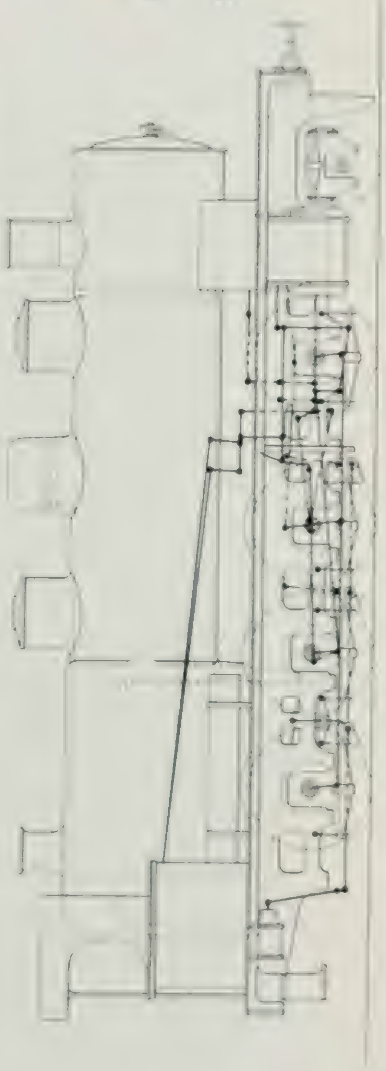
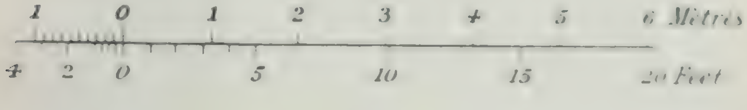


Fig. 11.
Nos. 4001—4002.
Est.
Cyls. H.P. 15⅛in.
L.P. 23⅝in.
× 25⅝in.





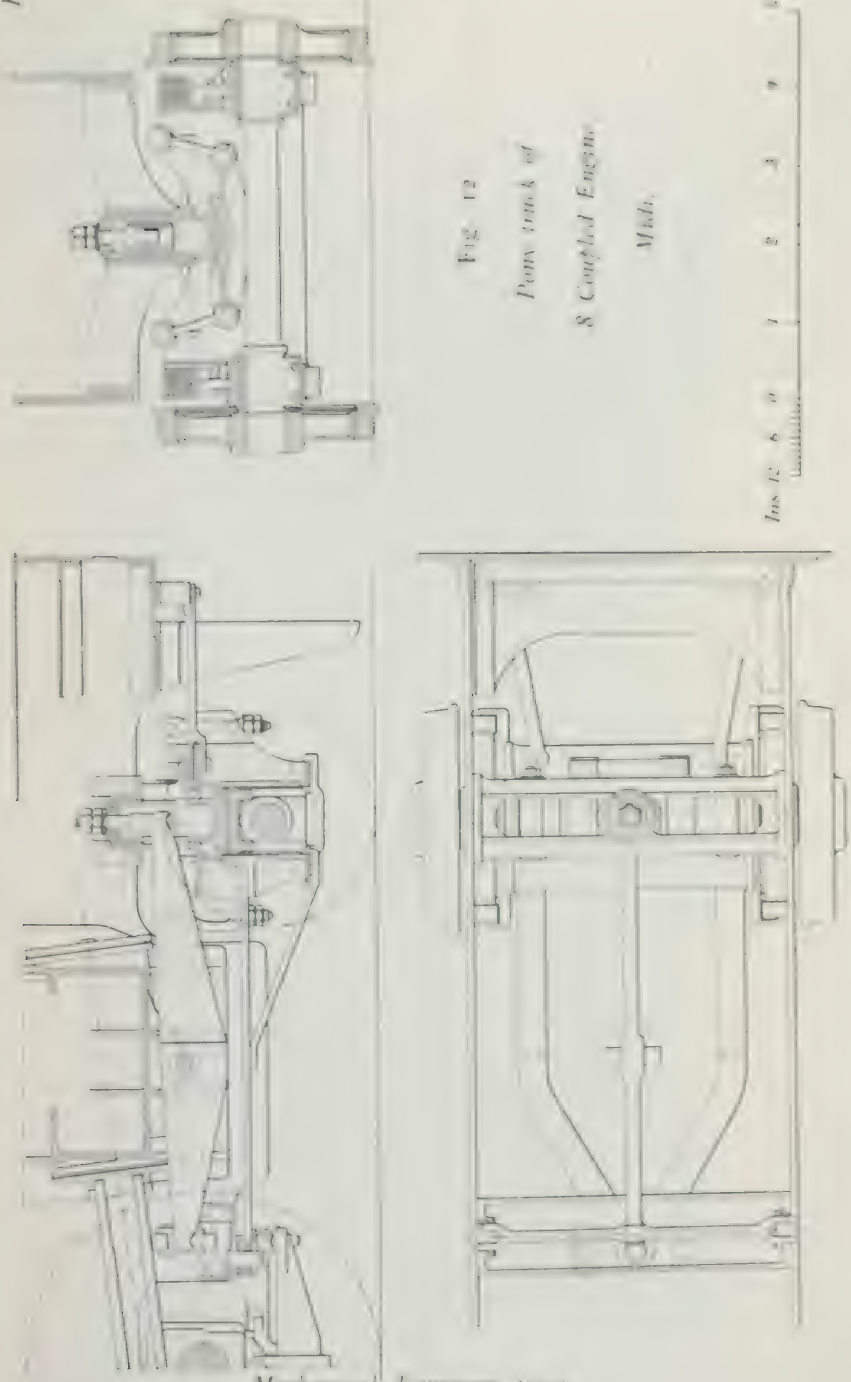


Fig. 12.

Pony truck of

8 Coupled Engine.

Midi.

COMPOUND LOCOMOTIVES IN FRANCE

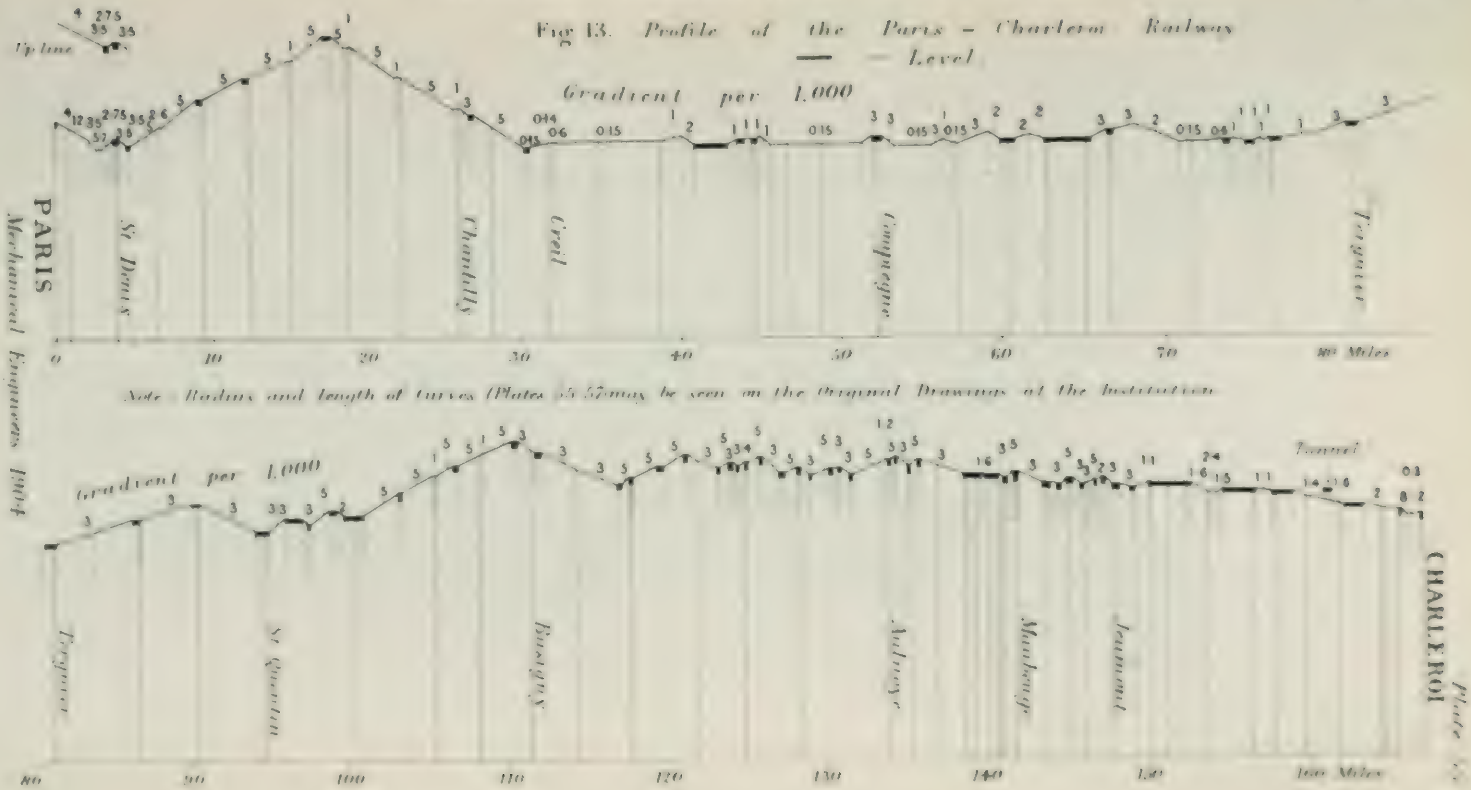


Fig 13. Profile of the Paris – Charleroi Railway

Note: Radius and length of Curves (Plates 55-57) may be seen on the Original Drawings at the Institution.

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COMPOUND LOCOMOTIVES IN FRANCE.

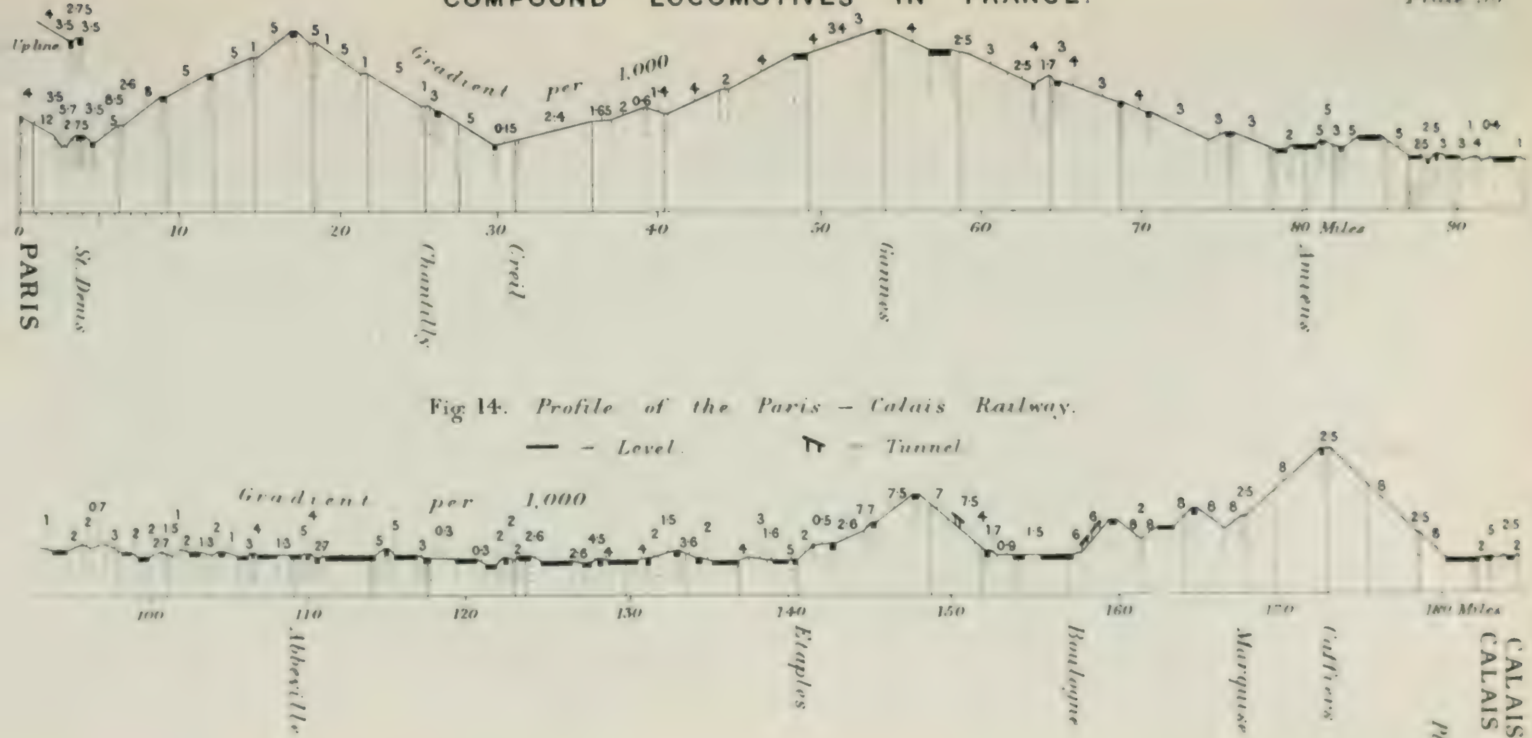

Fig. 14. *Profile of the Paris – Calais Railway.*

COMPOUND LOCOMOTIVES IN FRANCE

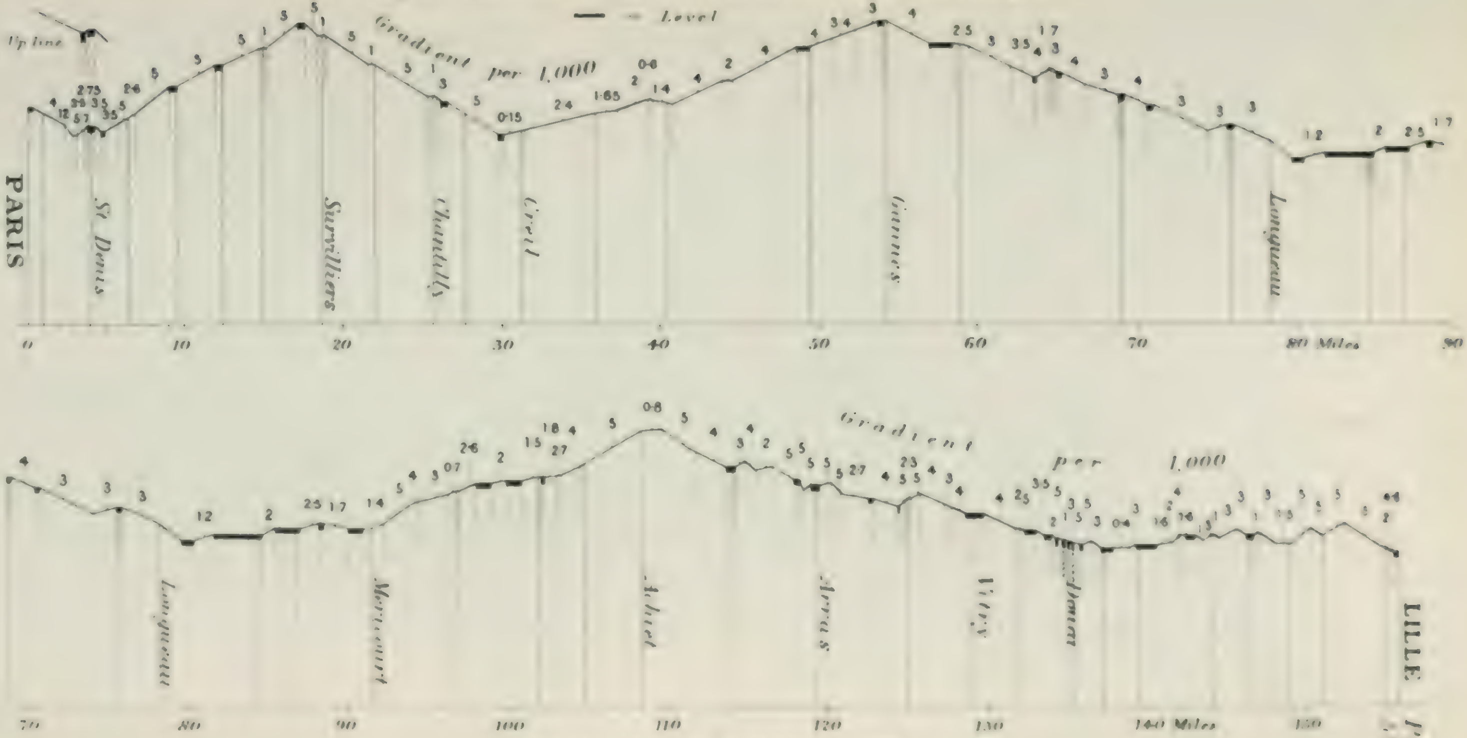

Fig. 15. *Profile of the Paris – Lille Railway*

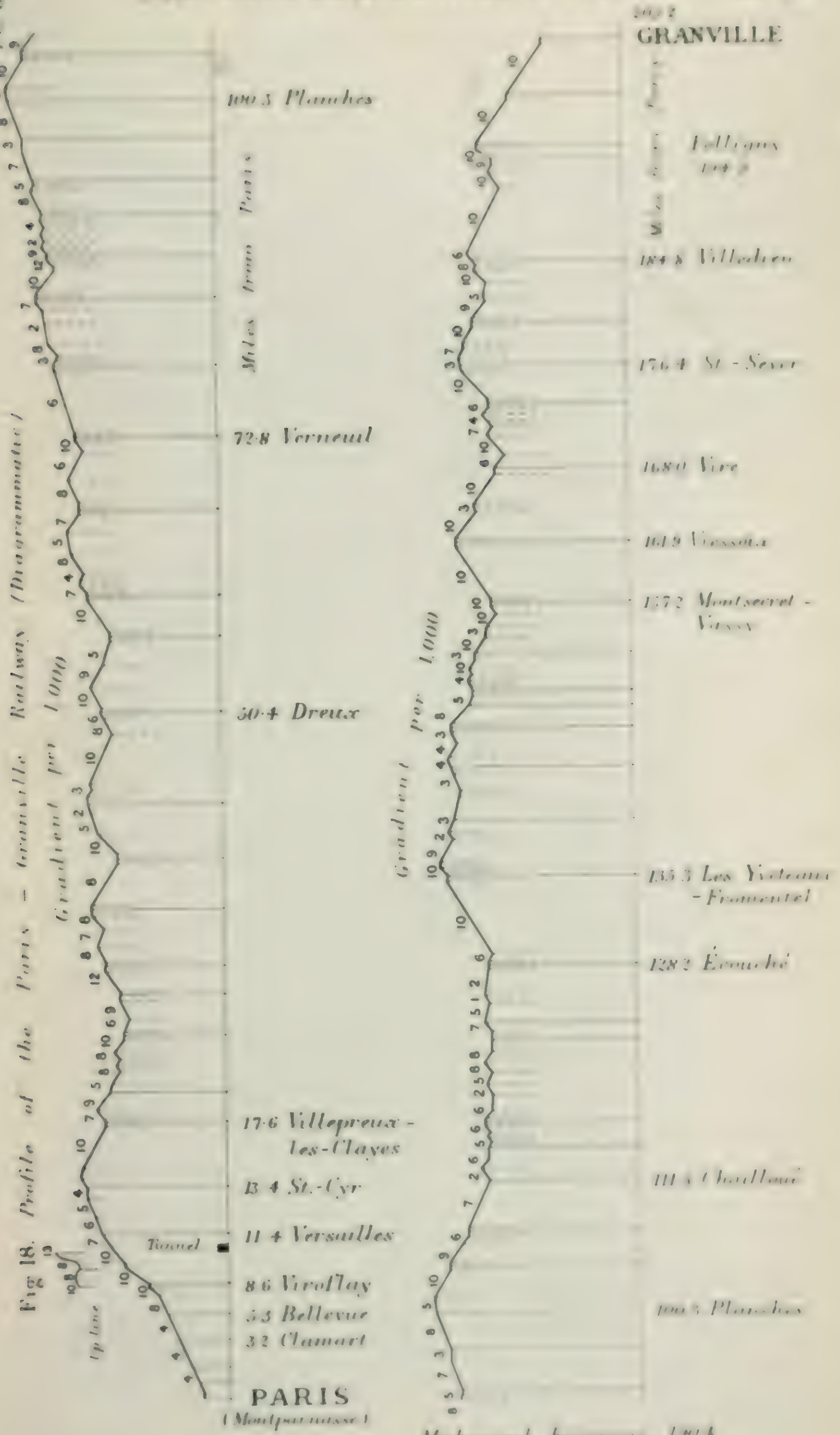

Fig. 18. *Profile of the Paris - Granville Railway (Diagrammatic)*

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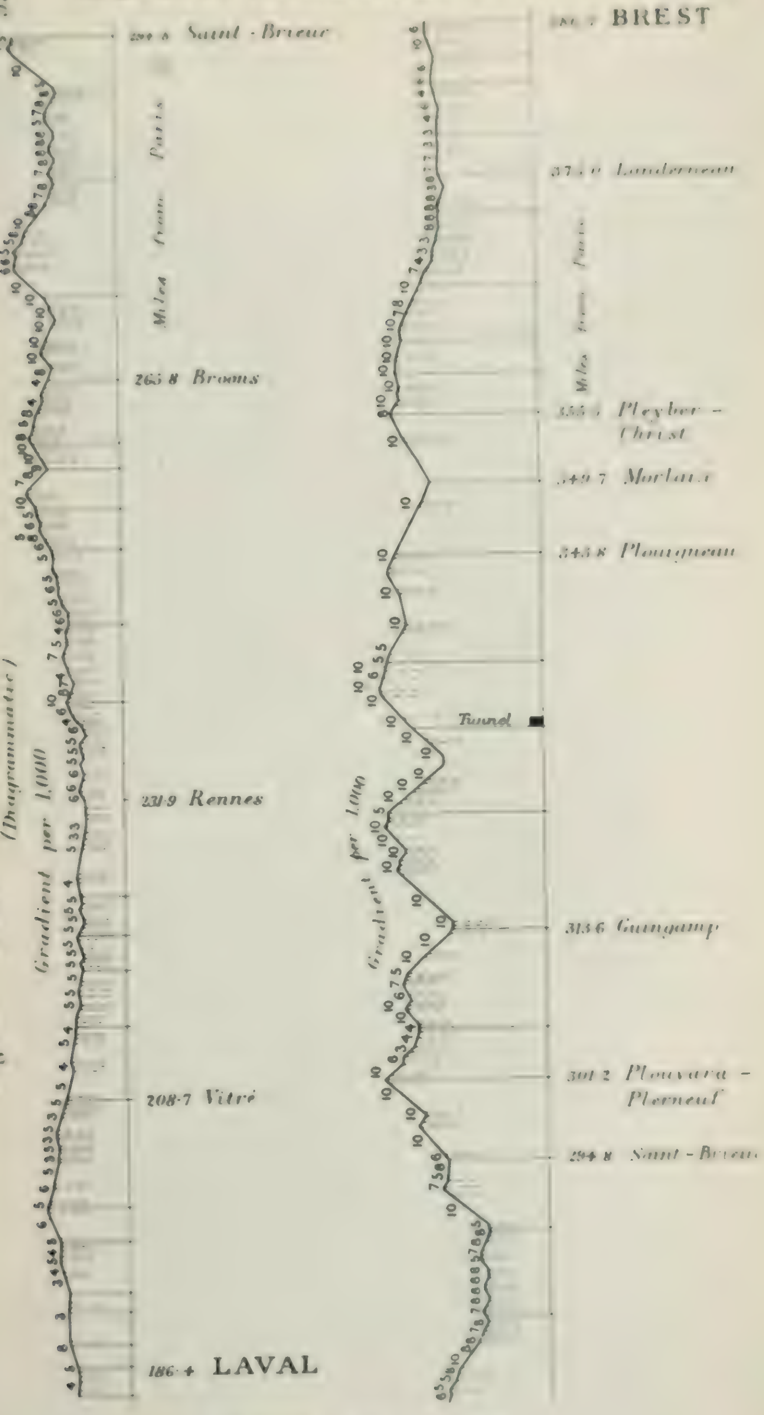
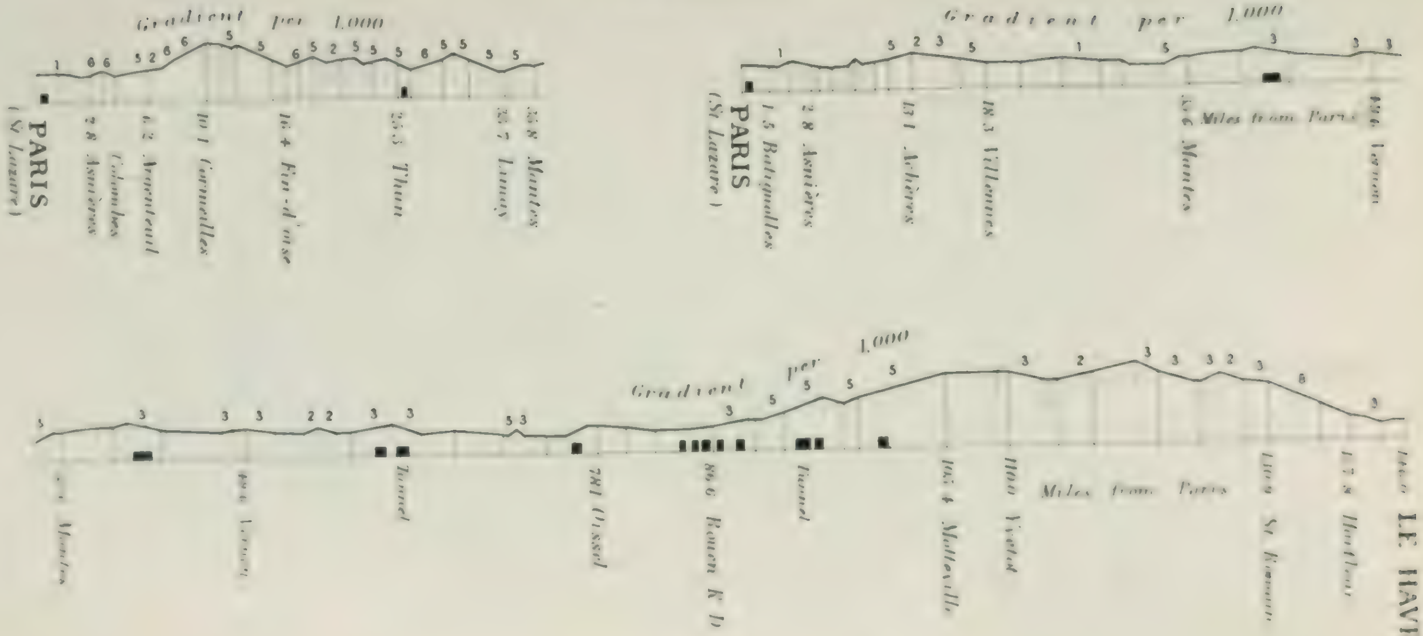


Fig 19. *Profile of the Laval - Brest Railway* *(Diagrammatic)*

COMPOUND LOCOMOTIVES IN FRANCE.

Fig 20 *Profile of the Paris – Le Hâvre Railway.*

(Diagrammatic)



Mechanical Engineers 1904.

COMPOUND LOCOMOTIVES IN FRANCE.

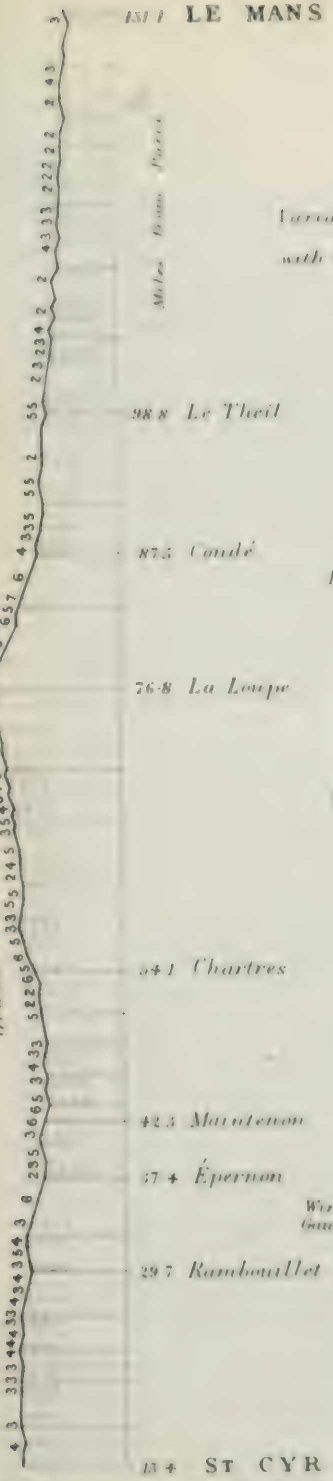


Fig. 21. Profile of the St Cyr – Le Mans Railway (Diagrammatic)

Paris to St Cyr, see Fig 18 Plate 58

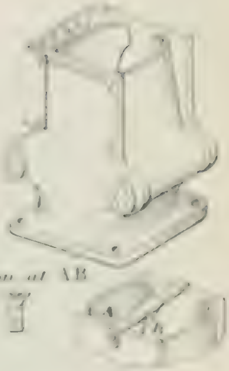


Fig. 22

Variable Blast Pipe with dividing edge

Oil Cups

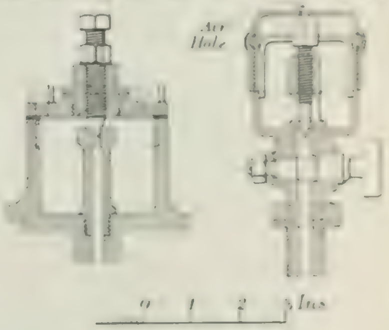


Fig. 23 For Moving Parts

Fig. 24 For Fixed Parts

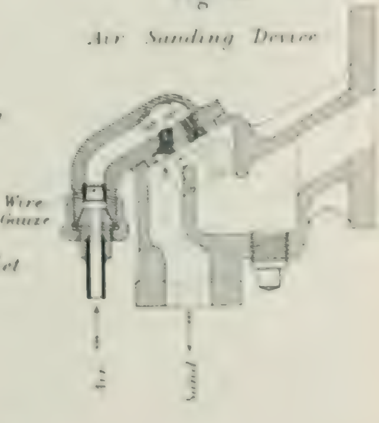


Fig. 25

Air Sanding Device

Mechanical Engineers 1904.

Walschaerts Valve Gear.

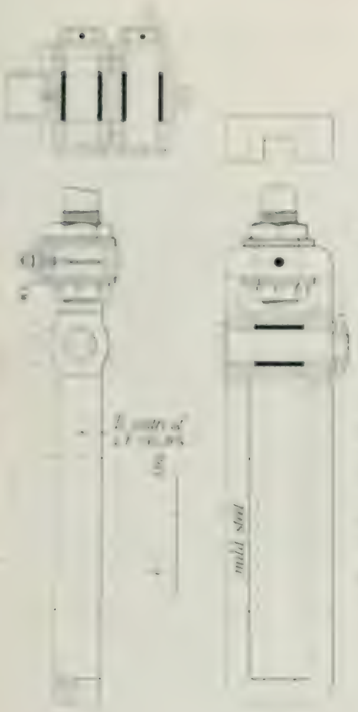
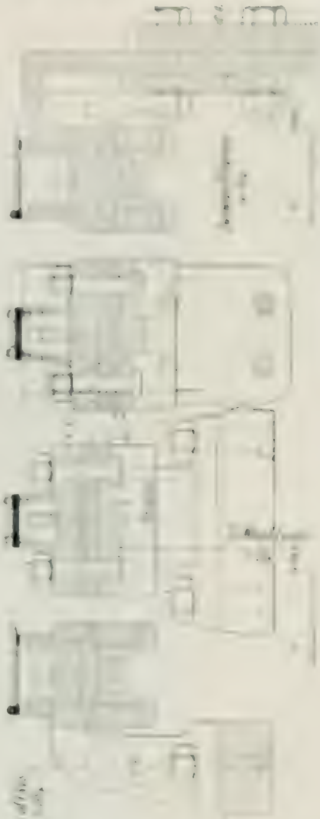


Fig. 27. Valve-Spindle Adjustment and Driving Connection.



Forked Guides for Valve-Spindles.

Fig. 28. H.P. Fig. 29. L.P.

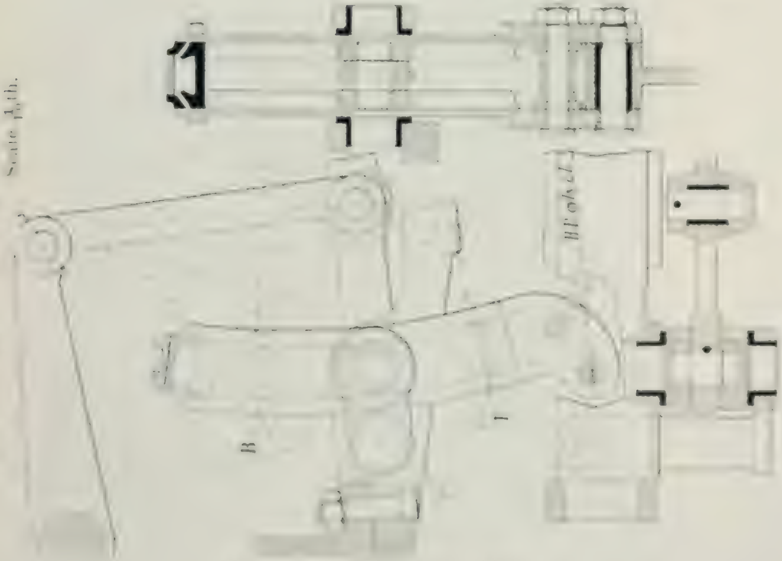


Fig. 26. Oscillating Link H.P. Scale 1/8th.

Steam pipe in Boiler

Fig. 30.
Spherical Joint in Boiler

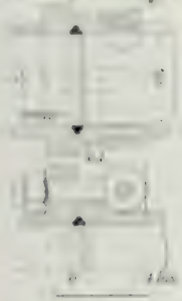


Fig. 31.
T-pipe [illegible] Boiler

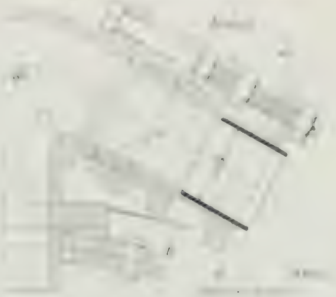
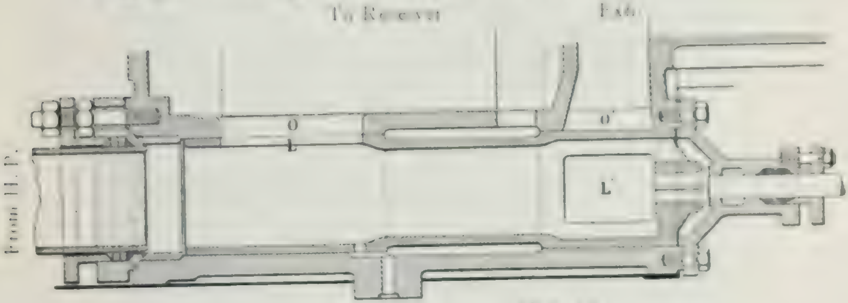


Fig. 32. *Starting Valve on top of L. P. Cylinder*



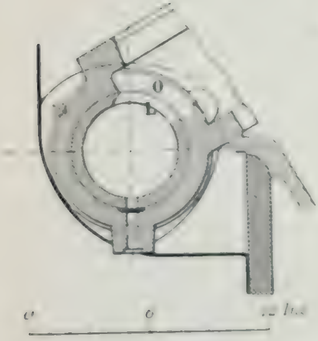
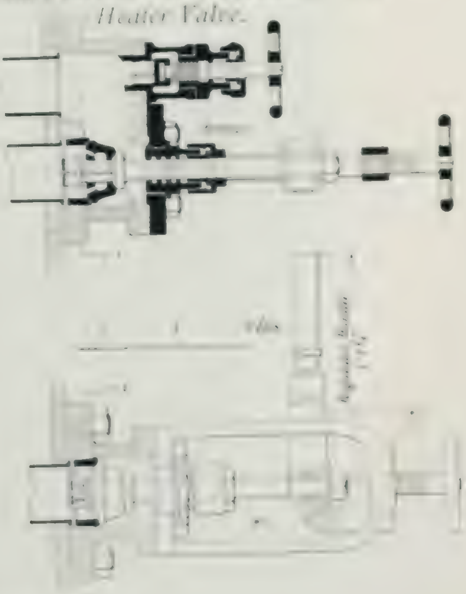


Fig. 33.
Auxiliary Steam Valve to Receiver and Heater Valve.



Mechanical Engineer 190[illegible]

Fig. 34. *Reversing Gear. H.P. and L.P.*
P.L.M. Nos. C. 61—130.

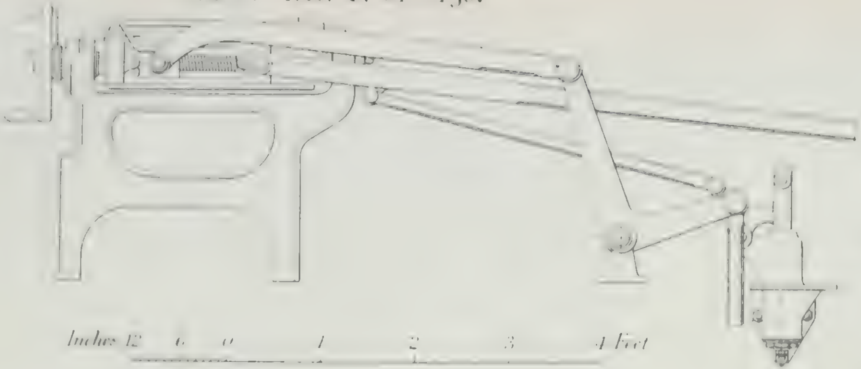


Fig. 35.
Ball Bearings
for
Reversing-Screw.

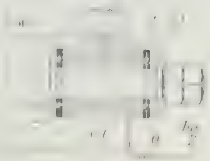


Fig. 36. *Piston Valve for H.P. Cyls.*
Est. Nos. 3501—3520.

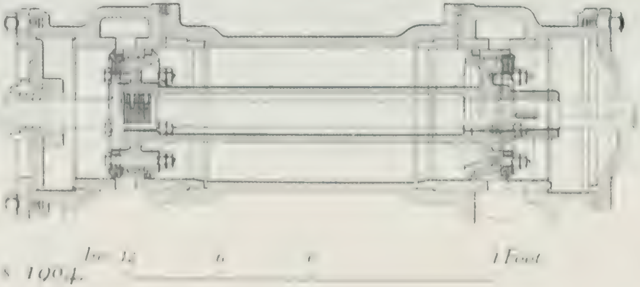
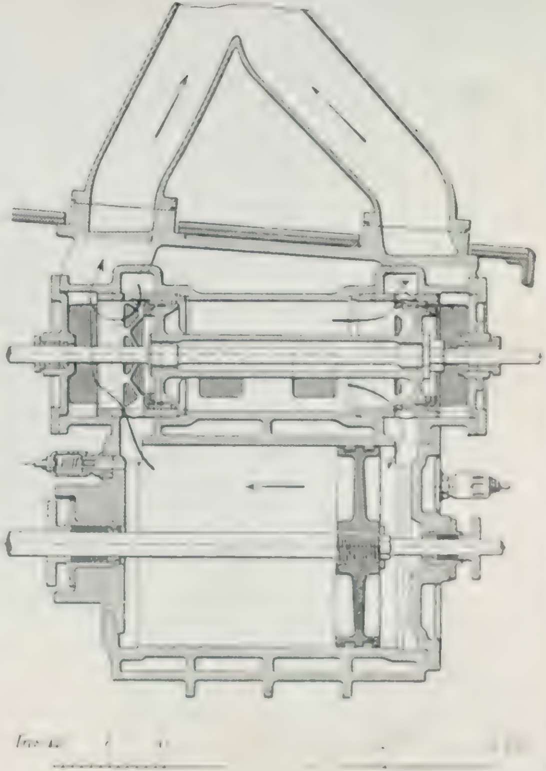


Fig. 37. *Piston Valve for L.P. Cyls.*
Est. Nos. 3501—3520



COMPOUND LOCOMOTIVES IN FRANCE.

(M. Lancrenon's remarks.)

Paris-Orléans.

Fig. 44. *Cyls. H.P. 14 $\frac{3}{16}$ in. L.P. 23 $\frac{5}{8}$ in. × 25 $\frac{5}{8}$ in. (See Fig. 5, Plate 51.)*

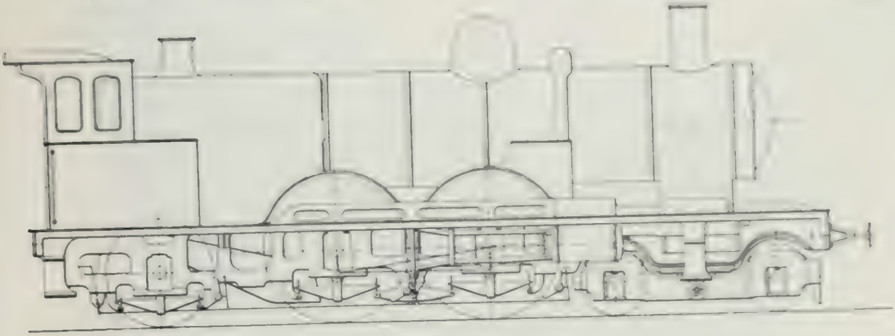


Fig. 45. *Cyls. H.P. 14 $\frac{3}{16}$ in. L.P. 23 $\frac{5}{8}$ in. × 25 $\frac{5}{8}$ in. (See Fig. 6, Plate 51.)*

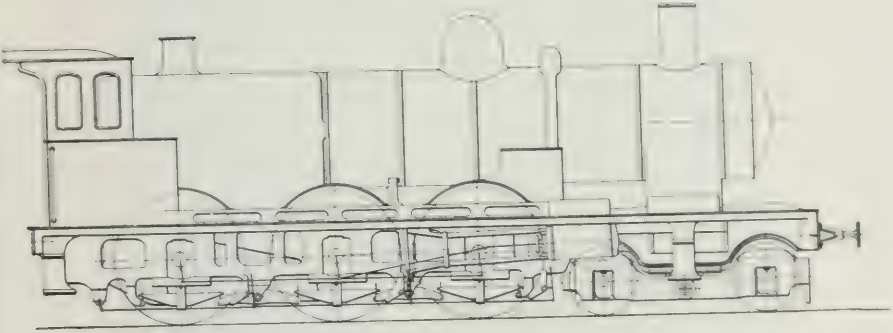
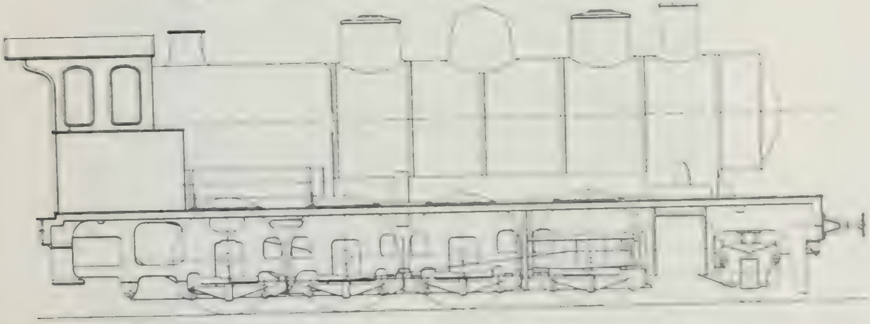
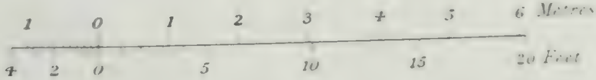


Fig. 46. *Cyls. H.P. 15 $\frac{3}{4}$ in. L.P. 23 $\frac{5}{8}$ in. × 25 $\frac{9}{16}$ in.*





$14 \times \frac{9}{5}$

$$\begin{array}{r} 1\,7 \\ 3\,2 \\ \hline 1\,9 \end{array}$$

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